Di-electron Production in Heavy-Ion Collisions at RHIC energies

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Many thanks to: Xiangli Cui, Xin Dong, Patrick Huck, Lijuan Ruan, Zebo Tang, Haojie Xu, Qun Wang and Jie Zhao

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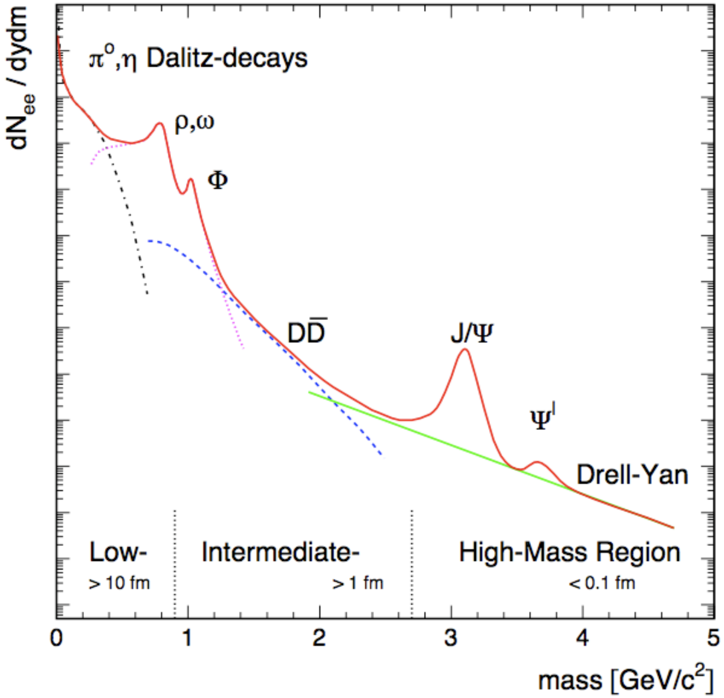
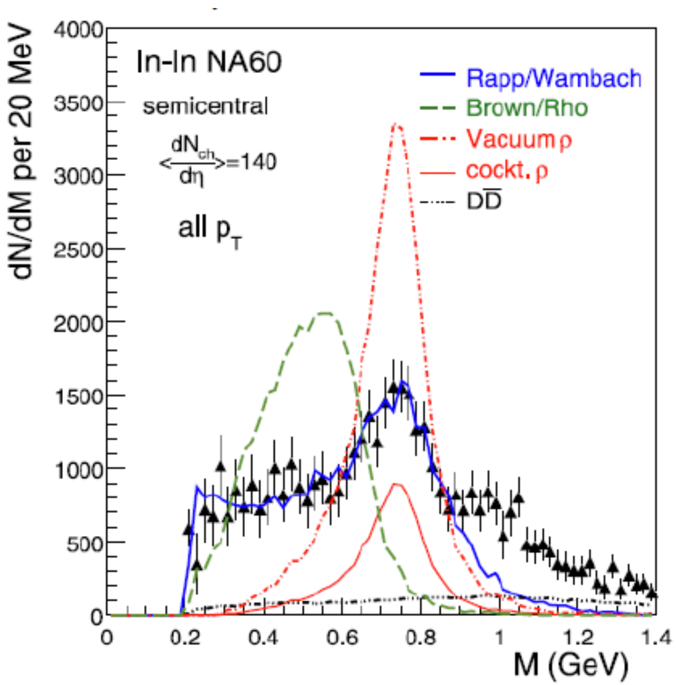
e-Forum on High-energy Nuclear Physics in China
10 Jan 2013

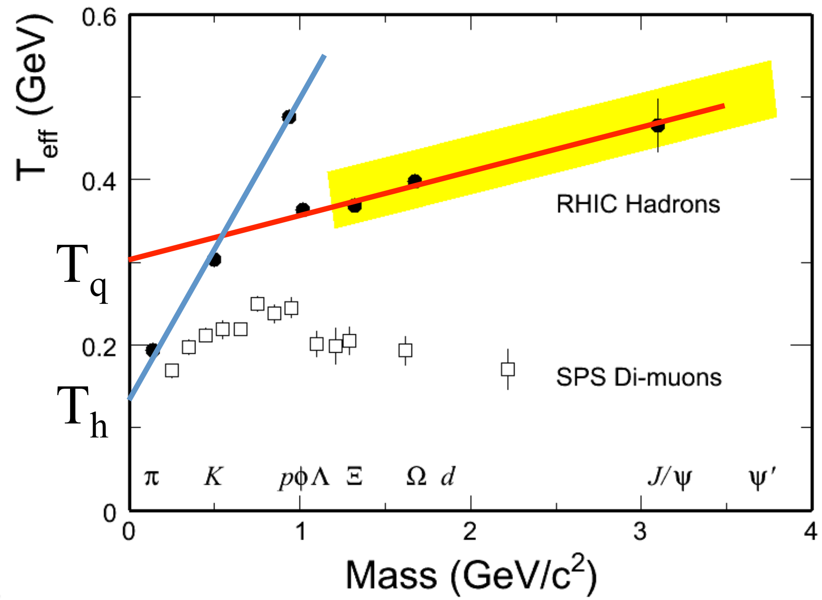
Outline

- Introduction.
- Analysis techniques.
- Cocktail simulations.
- Results and Discussions.
  - spectrum, LMR, IMR
  - v_2
- Summary.

Introduction - I







NA60: Eur.Phys.J.C59:607-623 (2009)

RHIC 200 GeV, NPA 757,102 (2005)

$$T_{\mathrm{eff}} = T_0 + M v_T^2$$

LMR Chiral symmetry restoration
Vector meson production: in-medium effect

IMR Heavy quark correlation
QGP thermal radiation

HMR Heavy quarkonia production
Drell-Yan

Electromagnetic probes =>

Do not participate in strong interactions.

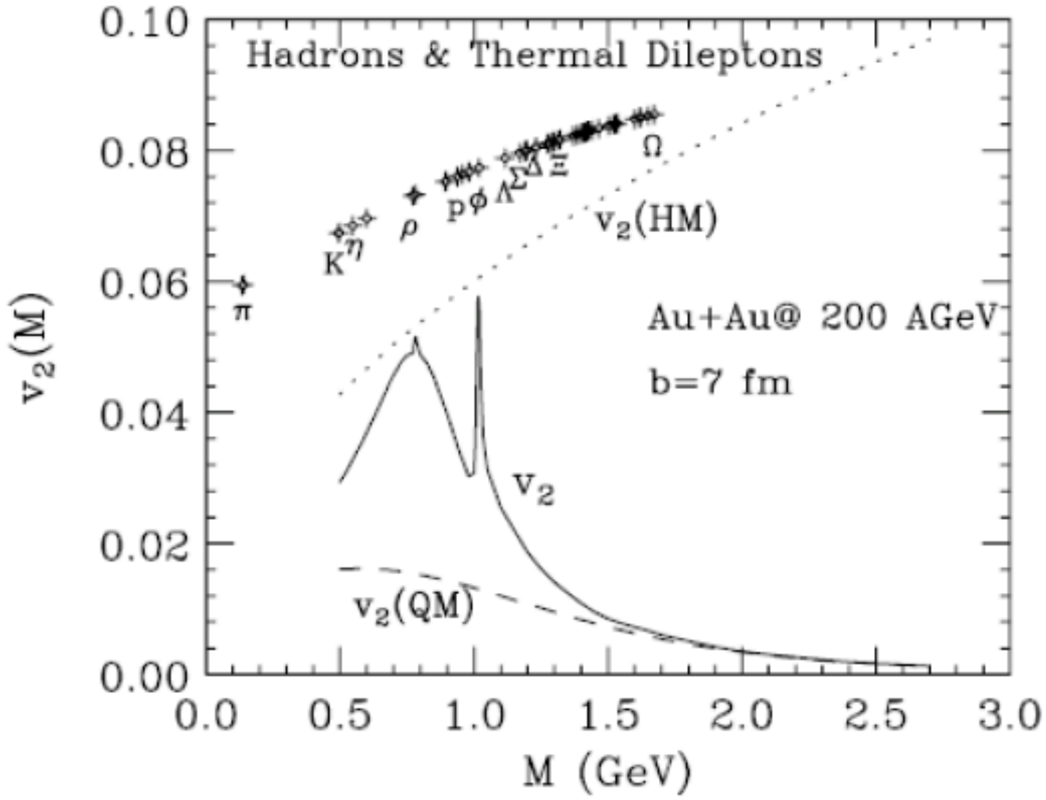
Bring undistorted information as where they are produced.

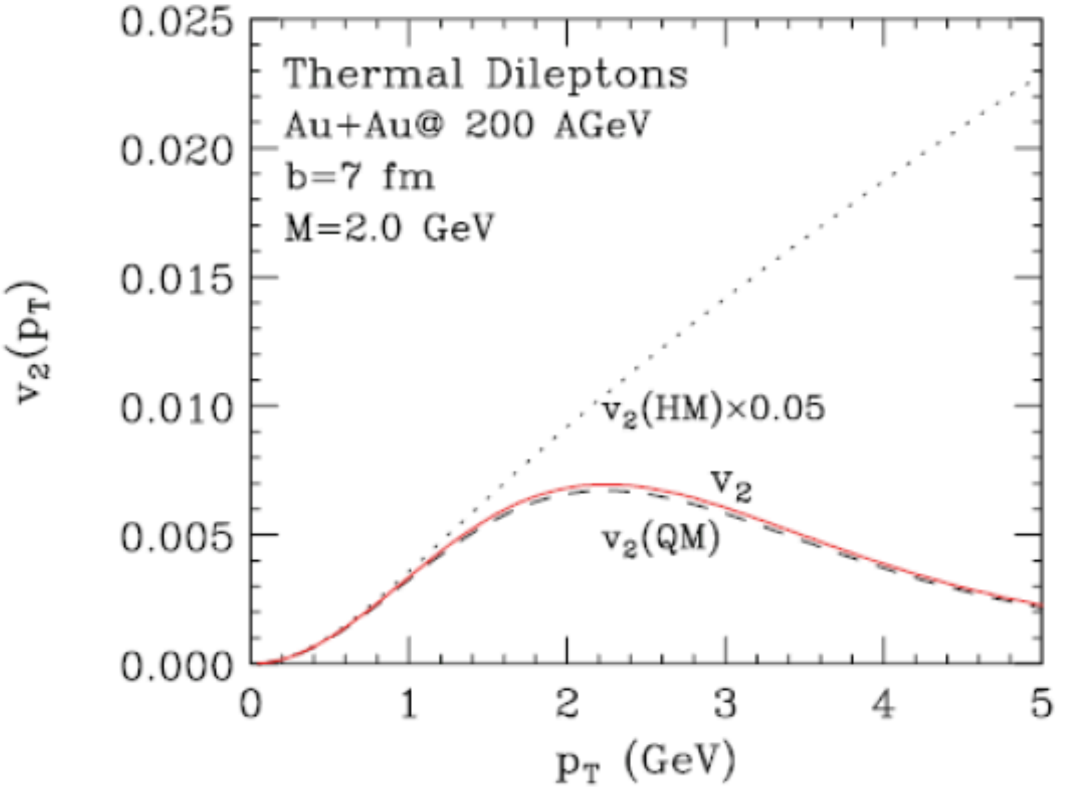
Penetrate medium properties.

Challenge: Time-space integrated from every stages.

Introduction - II

Rupa Chatterjee , et al., *Phys Rev C 75, 054909 (2007)*

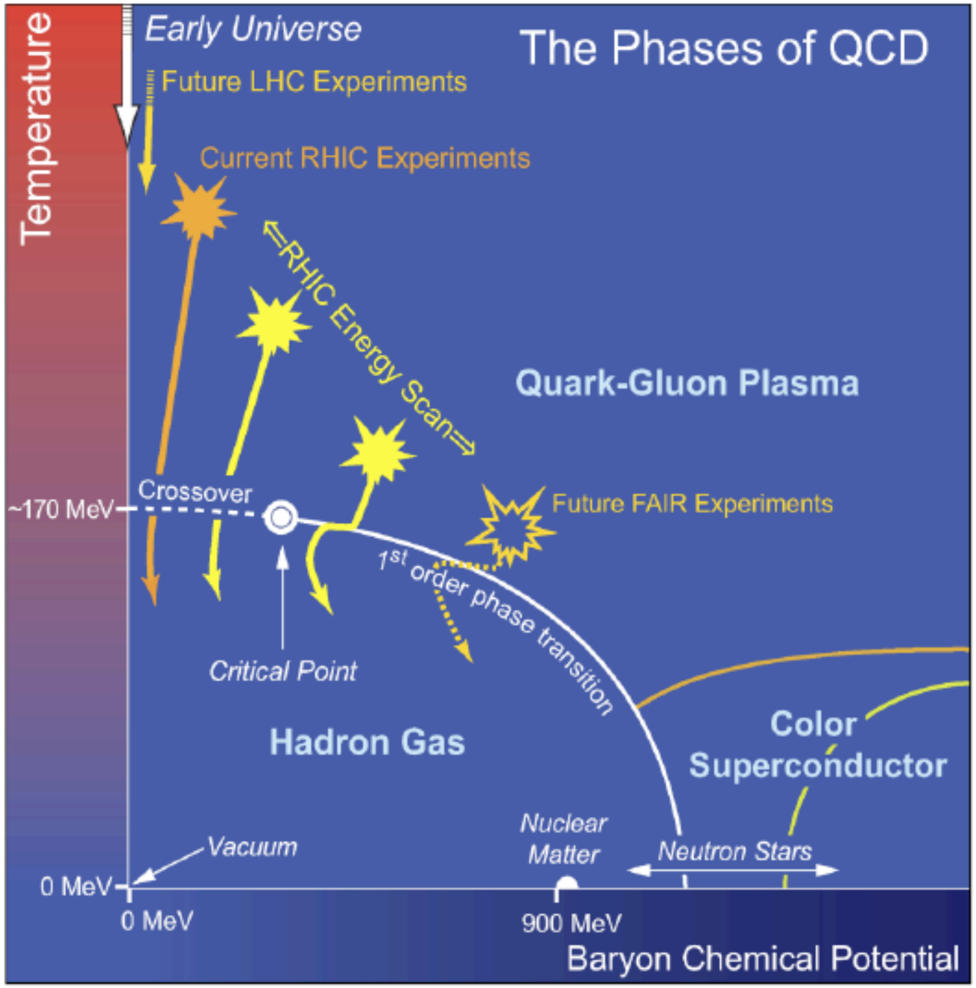




- Di-lepton produced in every stage of the time-space evolution, its v_2 contains integrated information of the fireball expansion.

- Its differential v_2 in (mass, p_T) dimension could help us distinguish partonic and hadronic radiation sources.

Introduction - III



RHIC Energy Scan Program:

- Mapping QCD phase boundary.
- Search for QCD critical point.

Observables: fluctuations, flow, correlations …

What about "di-lepton"?

- Mass spectra
- m_T slope
- v_2

How are the behaviors in HG/QGP phase:

- light meson freeze-out
- ρ meson
- charm correlation
- thermal di-leptons

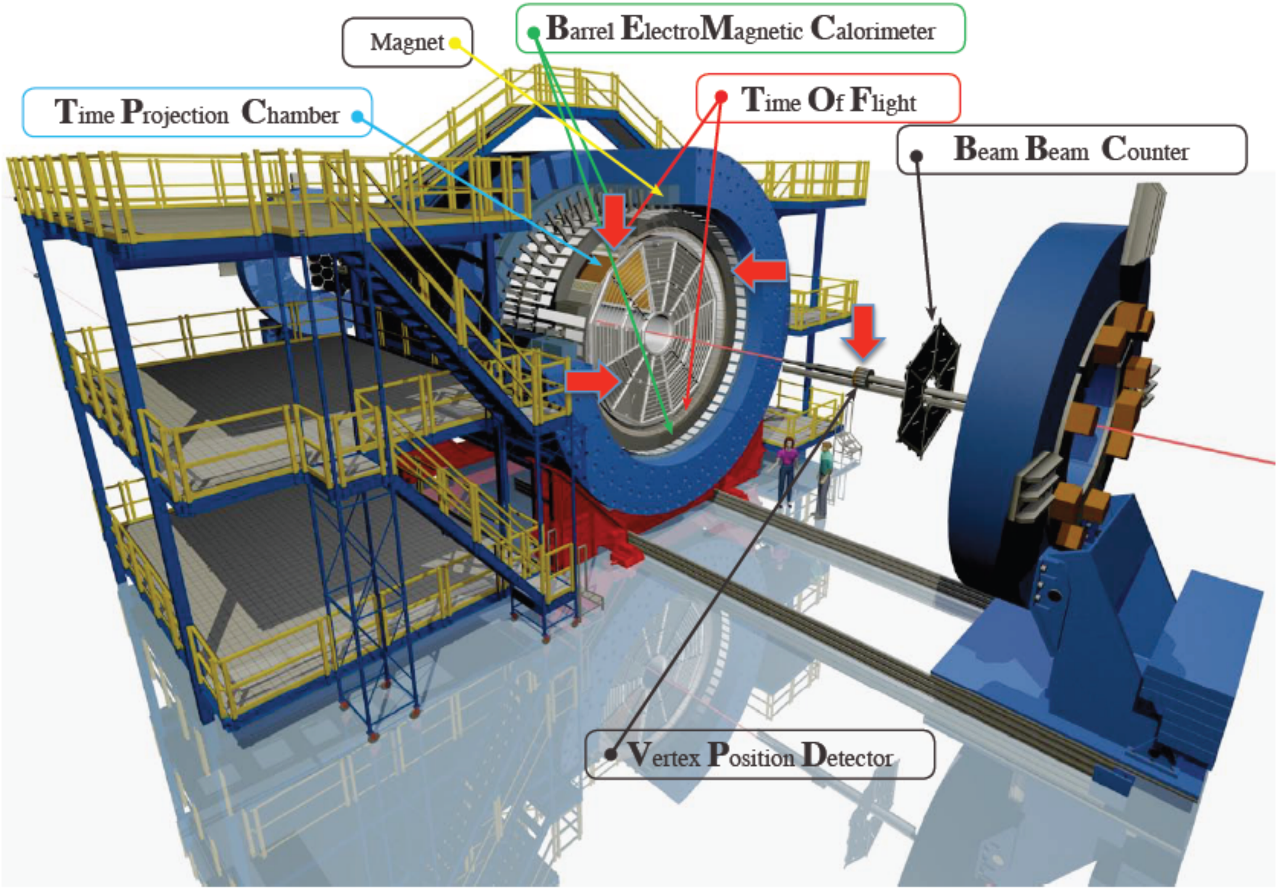
The STAR detector for di-lepton measurement

Time Projection Chamber:

- |eta|<1, full azimuth
- Tracking.
- PID through dE/dx

Time of Flight:

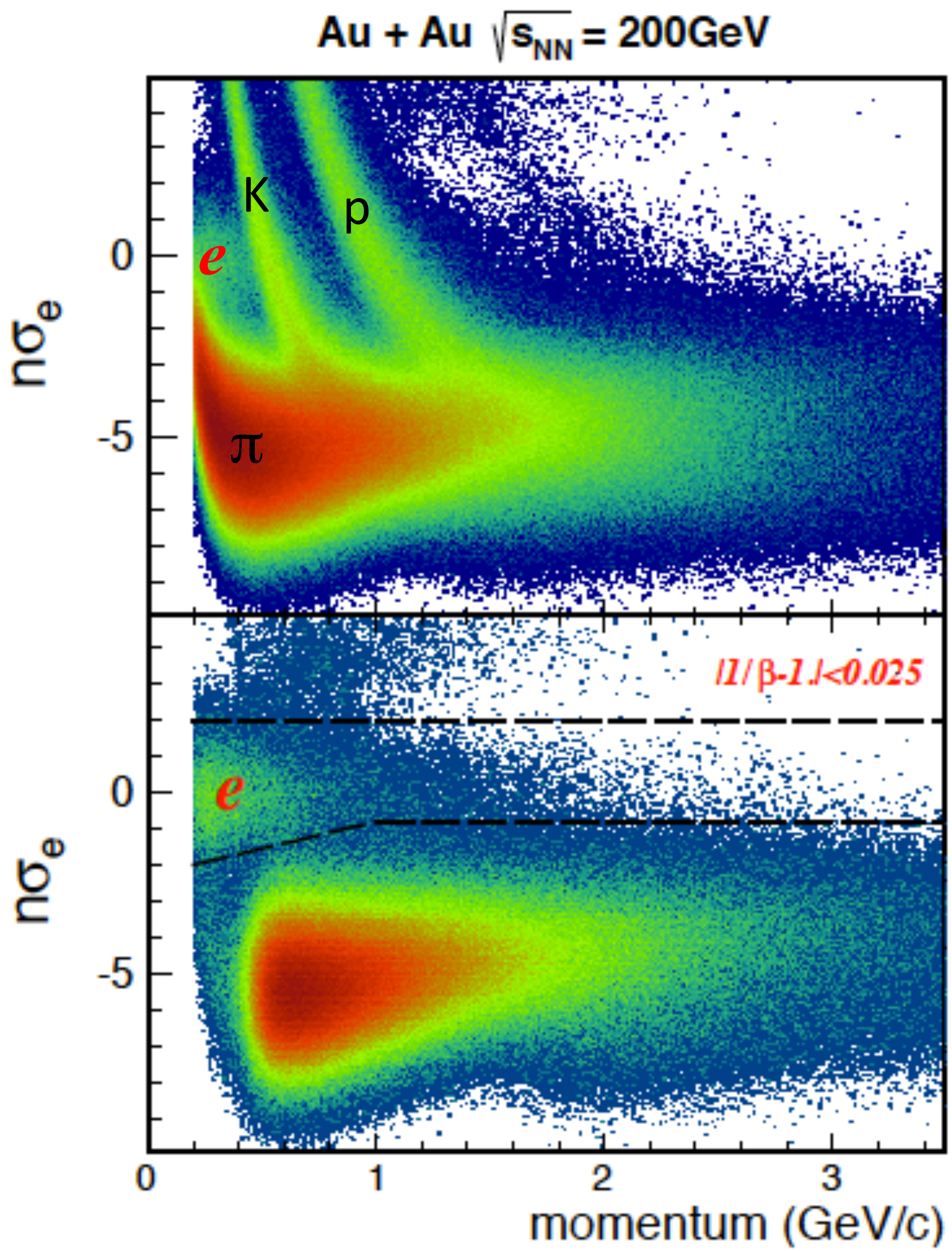
- |eta|<1, full azimuth .
- PID through TOF
- Timing resolution: ~85 ps.

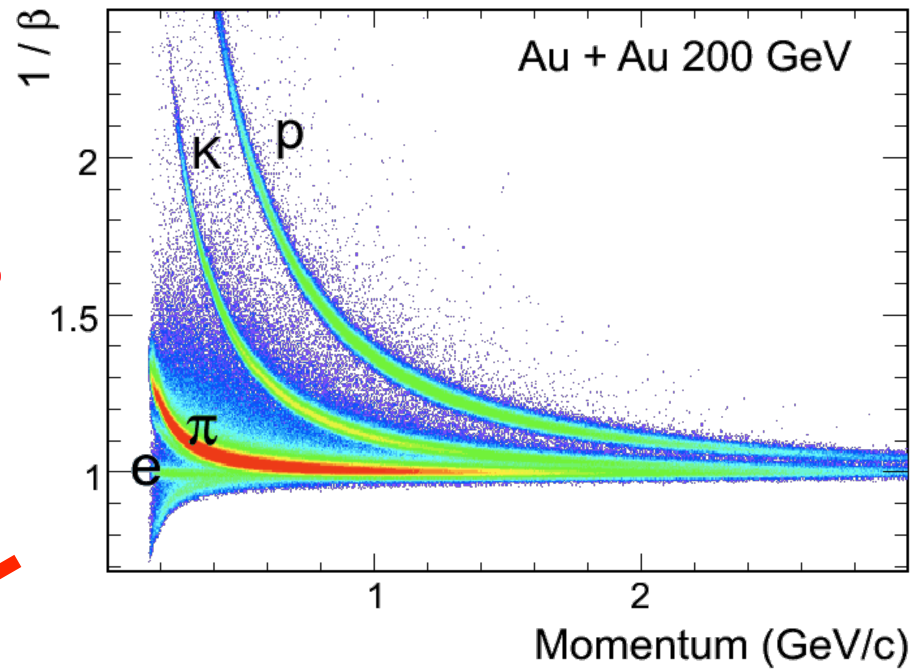


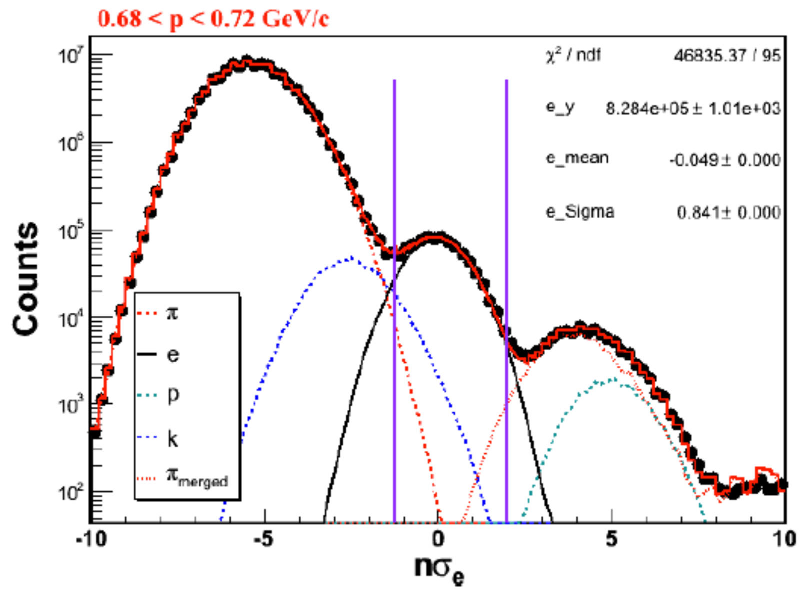
Barrel Electromagnetic Calorimeter

- |eta|<1, full azimuth
- **BTOW**:
  - Tower matching
  - p/E for electron ID
  - Fast online trigger
- **BSMD**:
  - Double layer High spatial resolution MWPC.
  - e/h separation.

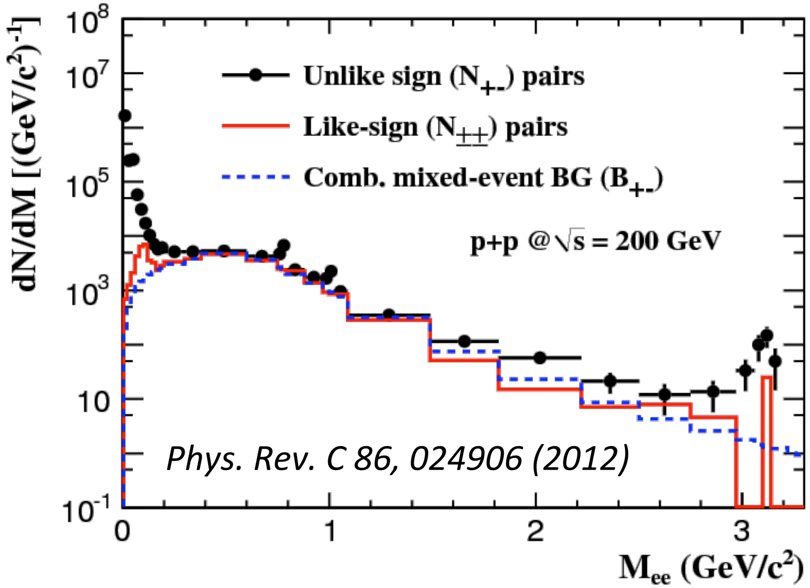
Electron Identification

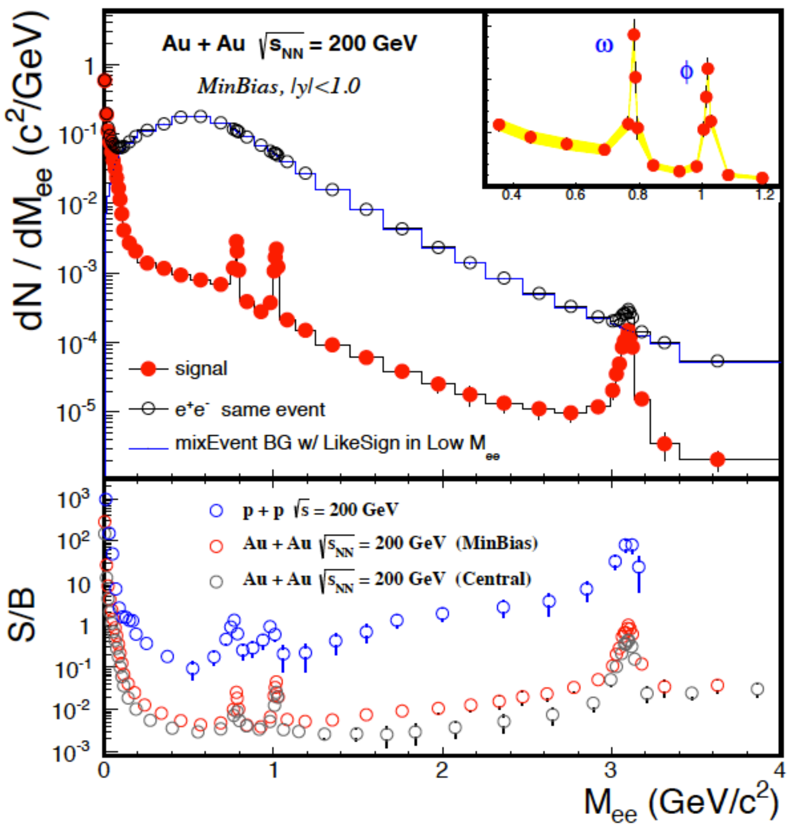






e^+e^- Invariant Mass & Background





Background sources

- combinatorial background (non-physical)
- correlated background *e.g.* double Dalitz decay, jet correlation.

Background methods

- like-sign: combinatorial & correlated BG
  - correct for acceptance differences
- mixed-event: combinatorial only
  - improve statistics
- background subtraction

  p+p: LS < 0.4 GeV/c^2 < ME

  Au+Au: LS < 0.75 GeV/c^2 < ME
- pair cuts remove photon conversions

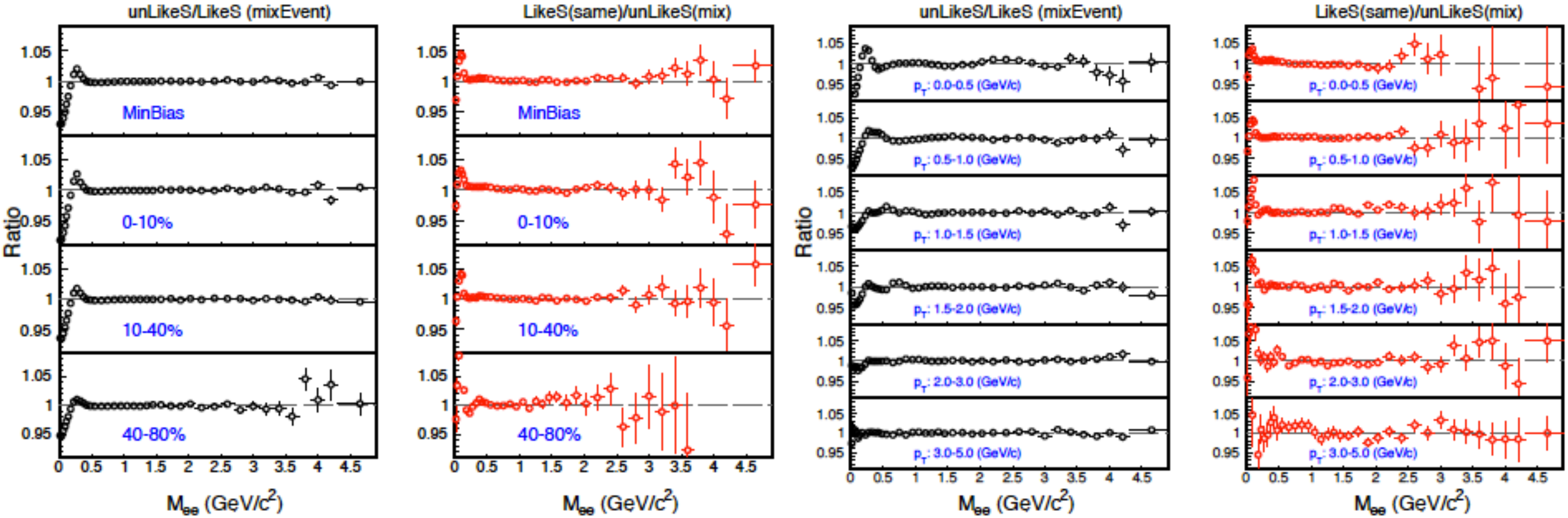
Signals (meson decays, medium modification, thermal radiation)

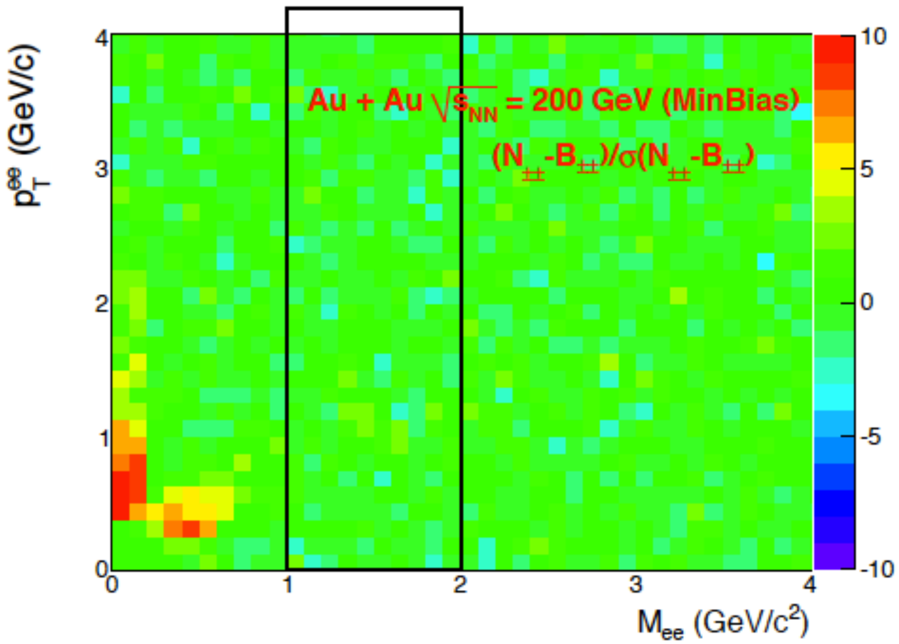
- Hadron simulation cocktail, models

S/B @ M_{ee}~ 0.5 GeV/c^2:

- 1/10 for p+p
- 1/250 for Au+Au central

Background Correction



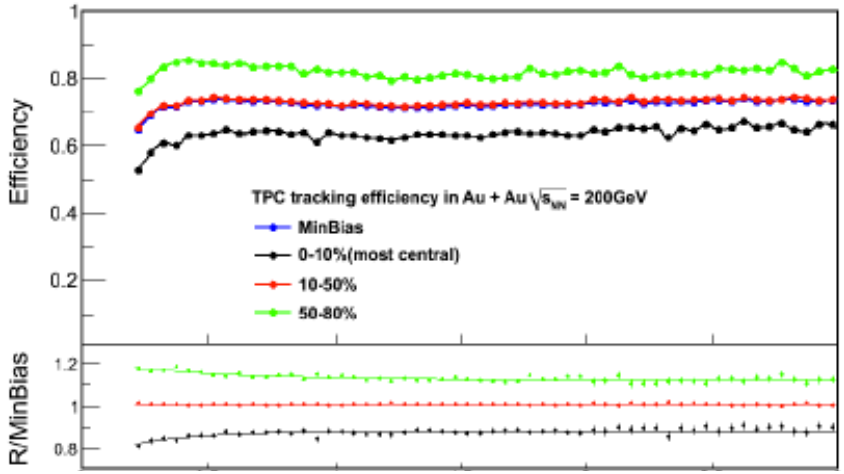


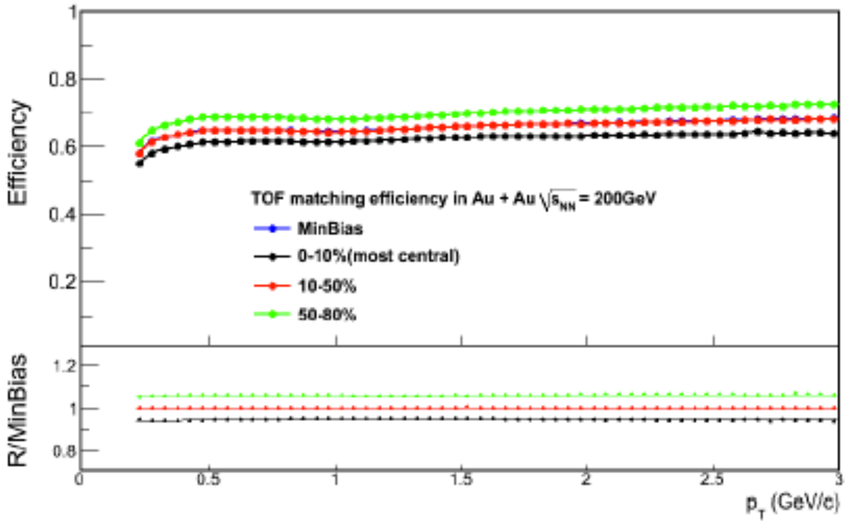
Like-sign background has been corrected by acceptance factor:

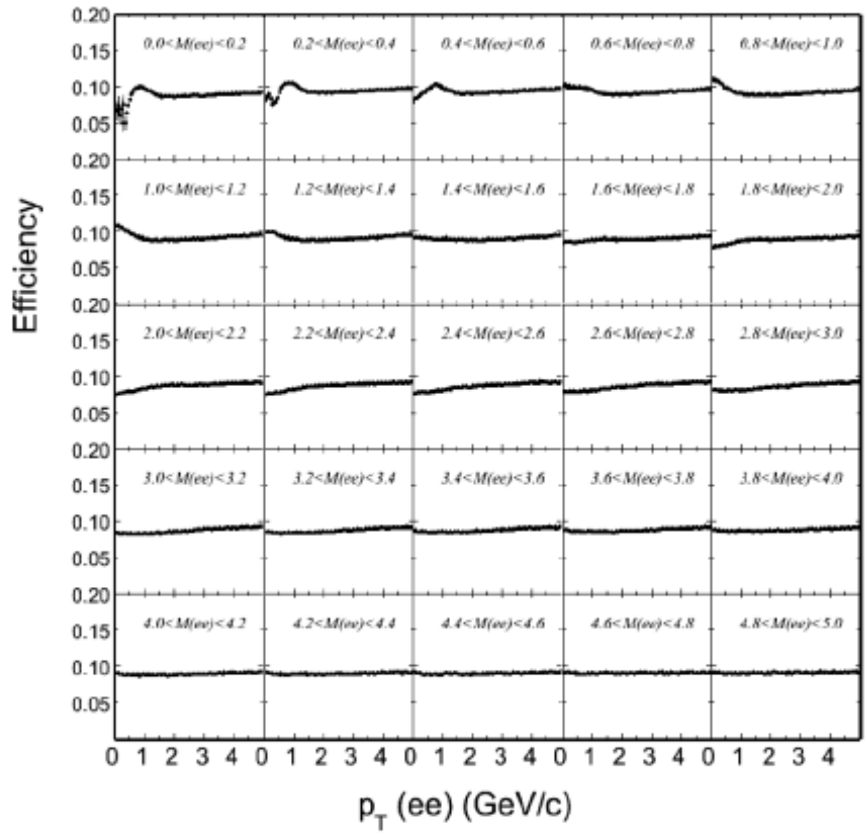
$$B_{+-}^{Mix} / (2\sqrt{B_{++}^{Mix} B_{--}^{Mix}})$$

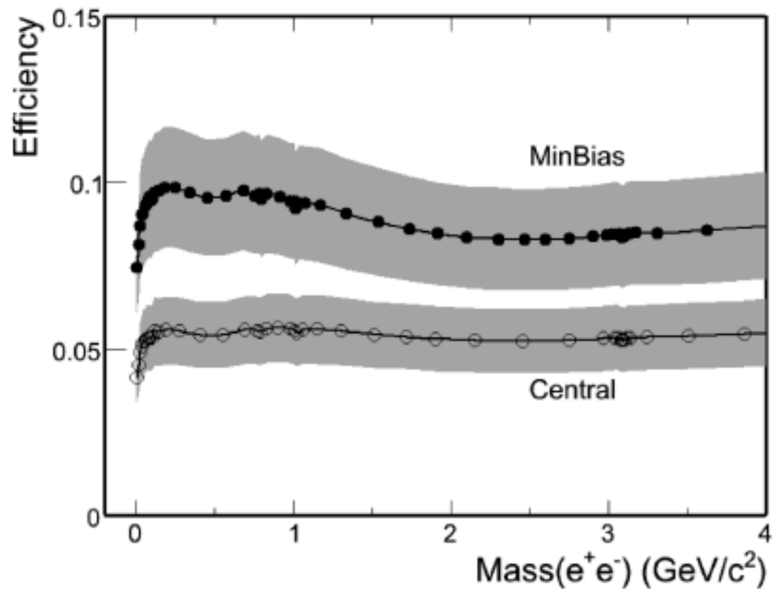
Corrections were done in each centrality and p_T bin.
Normalization in a random uniform region:

Efficiency unfolding







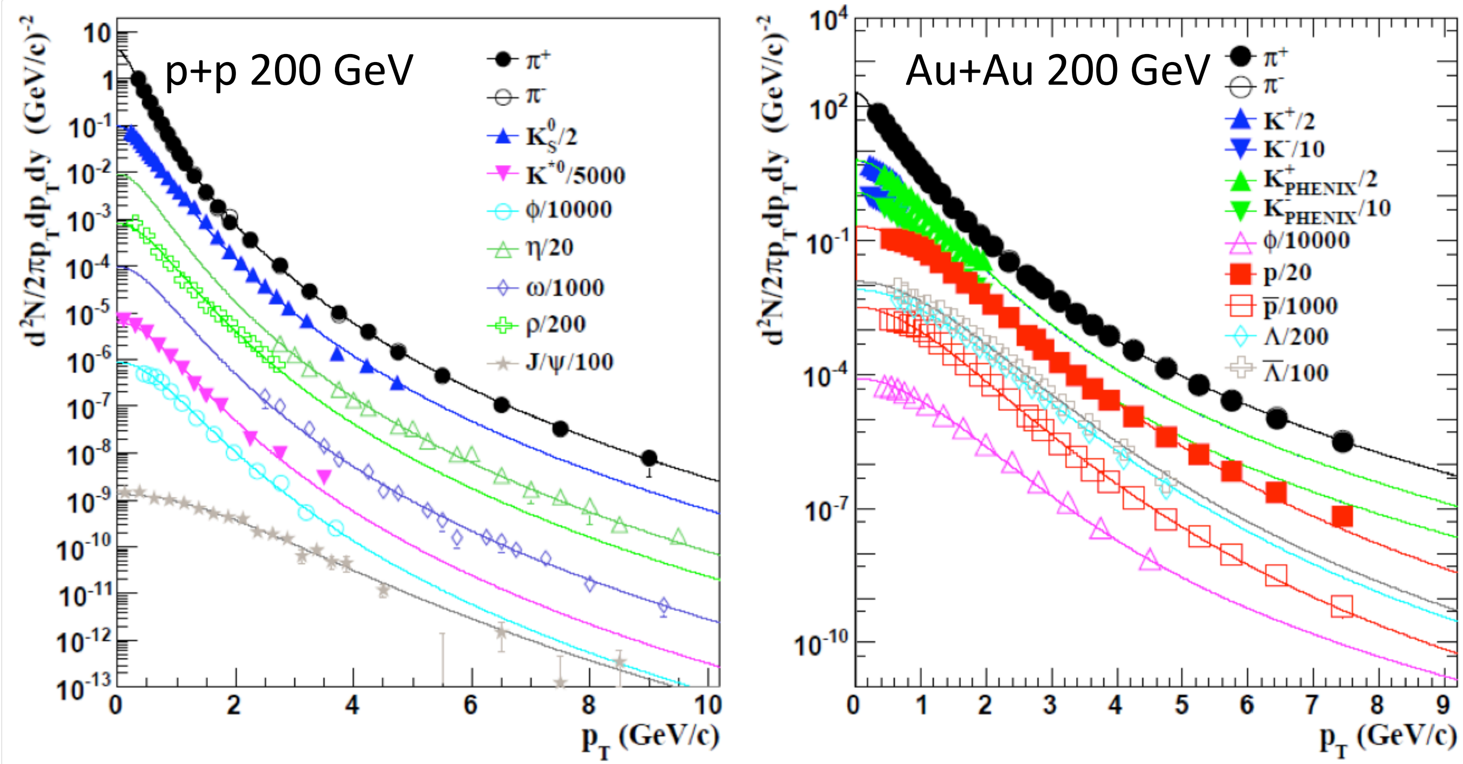


Efficiency: tracking, matching, cut

Each p_T, mass bin unfolding into final efficiency

Hadron decay cocktails

Input meson p_T spectra --- Tsallis Blast-Wave(TBW) fit to measurements.



$$\frac{dN}{m_T dm_T} \propto m_T \int_{-Y}^{+Y} cosh(y)dy \int_{-\pi}^{+\pi} d\phi \int_0^R rdr$$
$$\times(1 + \frac{q-1}{T}(m_T cosh(y)cosh(\rho) - p_T sinh(\rho)cos(\phi)))^{-1/(q-1)}$$

ρ is related to average flow velocity.
q-1 is the degree of non-equilibrium.
T is the freeze-out temperature.

Z. Tang, et.al., PRC79 051901 (R).

Hadron decay cocktails

Kroll-Wada Formula:

$$\frac{dN}{dm_{ee}} \propto \sqrt{1-\frac{4m_e^2}{m_{ee}^2}} \cdot \left(1+\frac{2m_e^2}{m_{ee}^2}\right) \cdot \frac{1}{m_{ee}} \cdot \left(1-\frac{m_{ee}^2}{M_h^2}\right)^3 |F(m_{ee}^2)|^2$$

QED | Phase Space | Form Factor

N.M. Kroll, et al., Phys Rev, 98 (1955) 5.

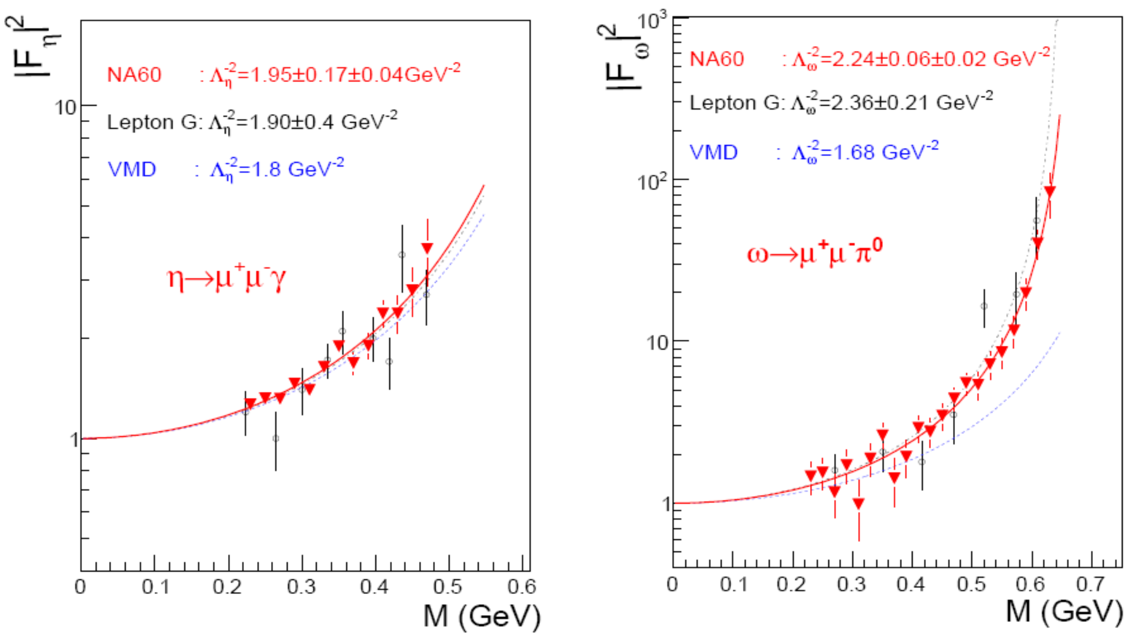
Two-body: Breit-Wigner

Dalitz: Kroll-Wada

FF: parameterized from measurement.

Phase Space term for ω, ϕ:

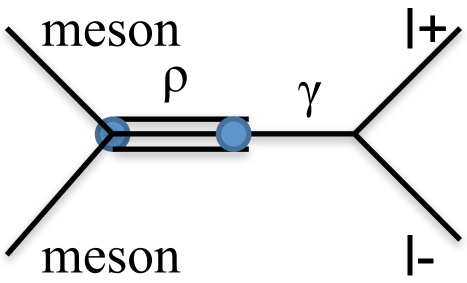
$$(1-\frac{m_{ee}^2}{m_h^2})^3 \rightarrow ((1+\frac{m_{ee}^2}{m_\omega^2-m_{\pi^0}^2})^2-\frac{4m_\omega^2 m_{ee}^2}{(m_\omega^2-m_{\pi^0}^2)^2})^{\frac{3}{2}}$$

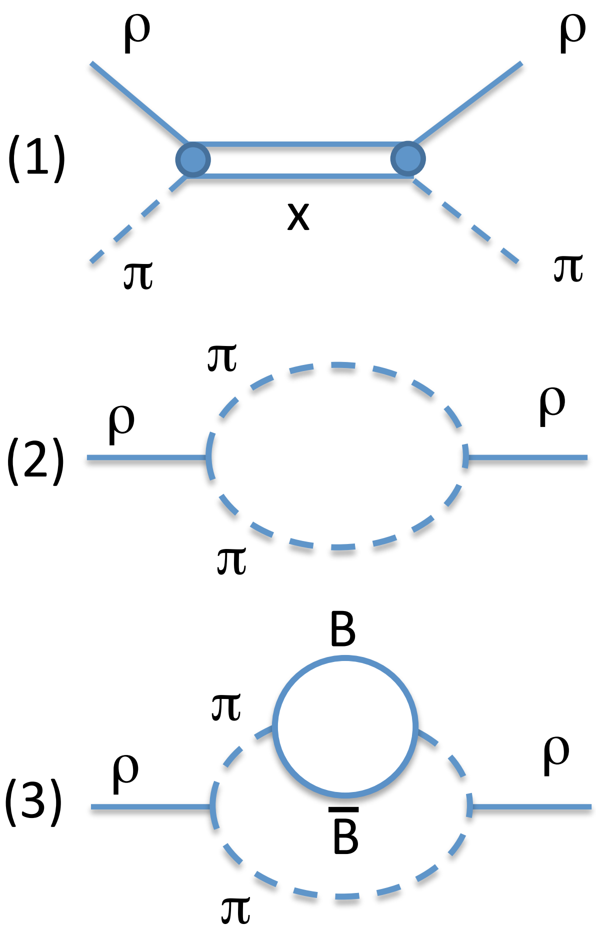


$$|F(m_{ee}^2)|^2 = \frac{1}{(1-m_{ee}^2\cdot\Lambda^{-2})^2+\Gamma_0^2\cdot\Lambda^{-2}}$$

NA60: PLB677 (2009) 260.

ρ broadening





ρ self-energy changes due to interactions with medium.

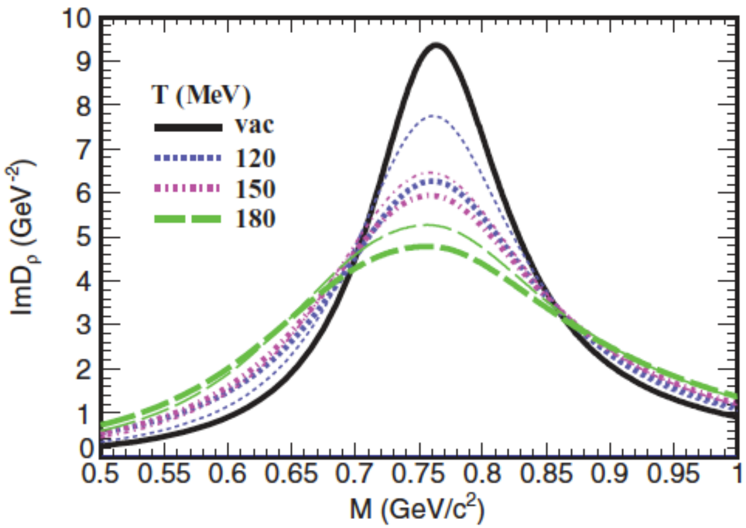
ρ interaction with meson gas.

ρ pionic decays.

pion-baryon scatterings.

Emission rate:
$$\frac{dN_{ll}}{d^4x d^4p} = -\frac{\alpha}{4\pi^4}\frac{1}{M^2} n_B(p\cdot u)\left(1+\frac{2m_l^2}{M^2}\right) \times\sqrt{1-\frac{4m_l^2}{M^2}}\,\mathrm{Im}\Pi^R(p,T).$$

V-m propagator:
$$\mathrm{Im}D_V^R = \frac{\mathrm{Im}\Pi_V^R}{\left(p^2 - m_V^2 + \mathrm{Re}\Pi_V^R\right)^2 + \left(\mathrm{Im}\Pi_V^R\right)^2},$$

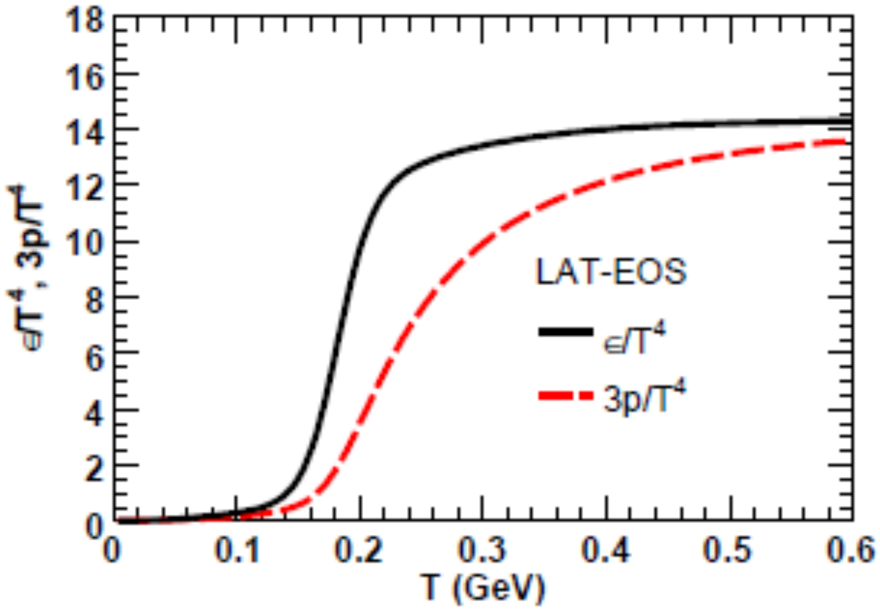


H. Xu, *et al.*, Phys. Rev. C 85 024906 (2012)

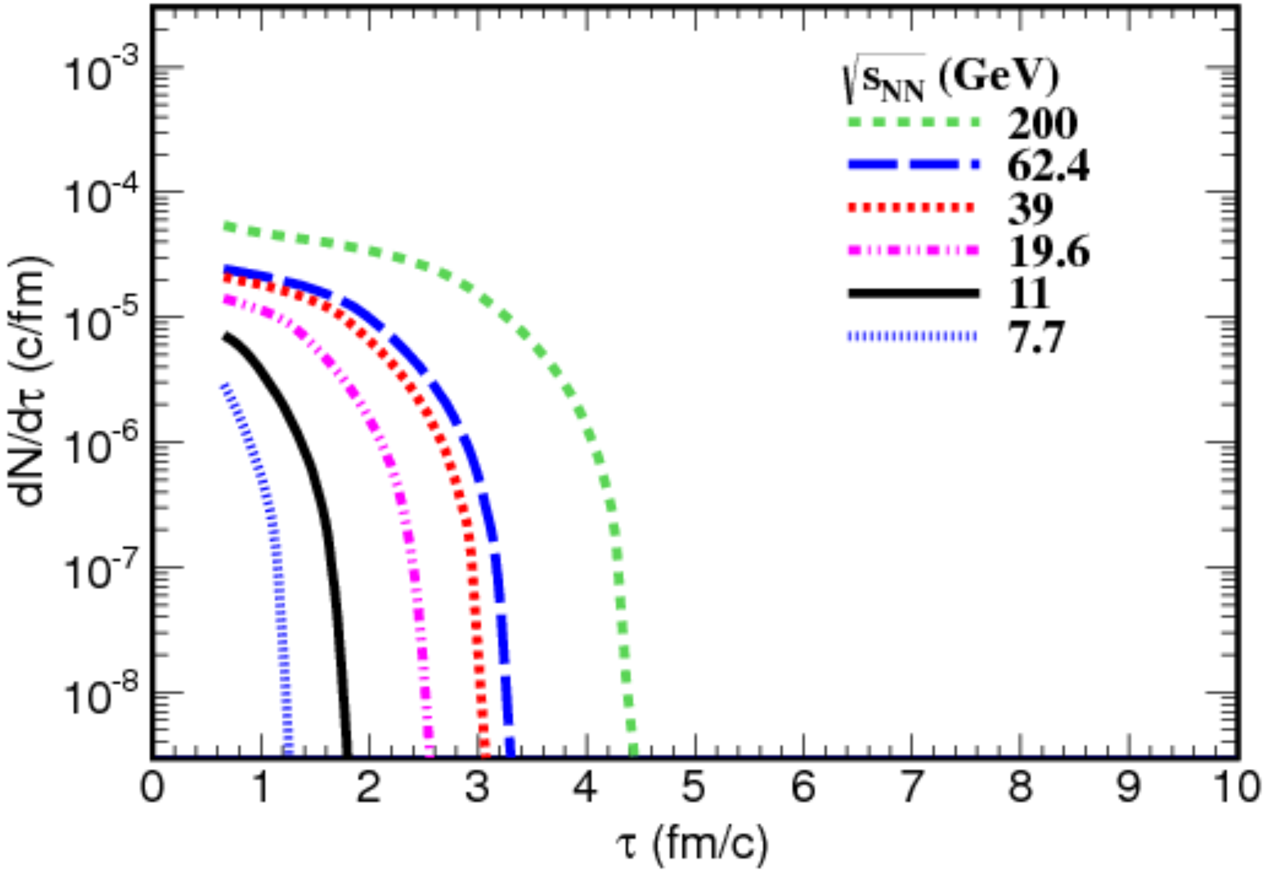
Space-time evolution

B. Schenke, et. al., PRC82, 014903 (2010)

(2+1)D ideal hydrodynamics
Lattice EOS
Parameters: S95P-PCE

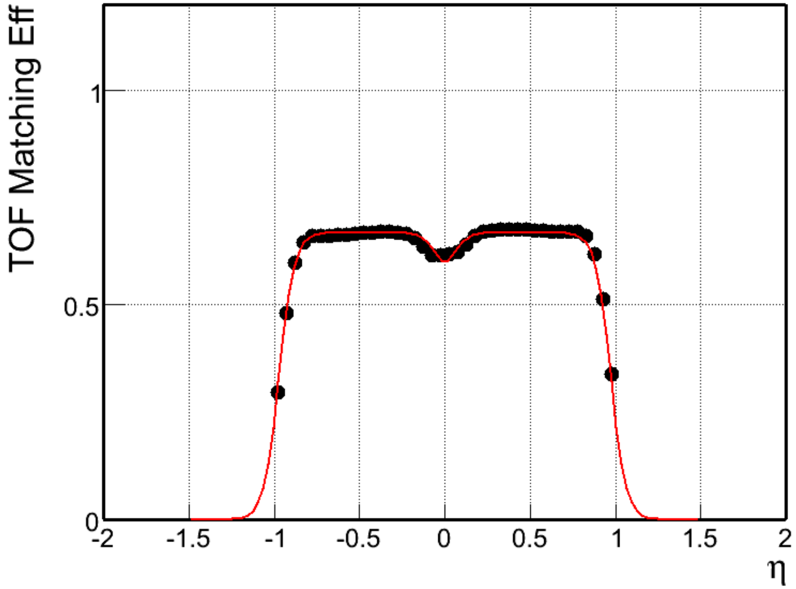


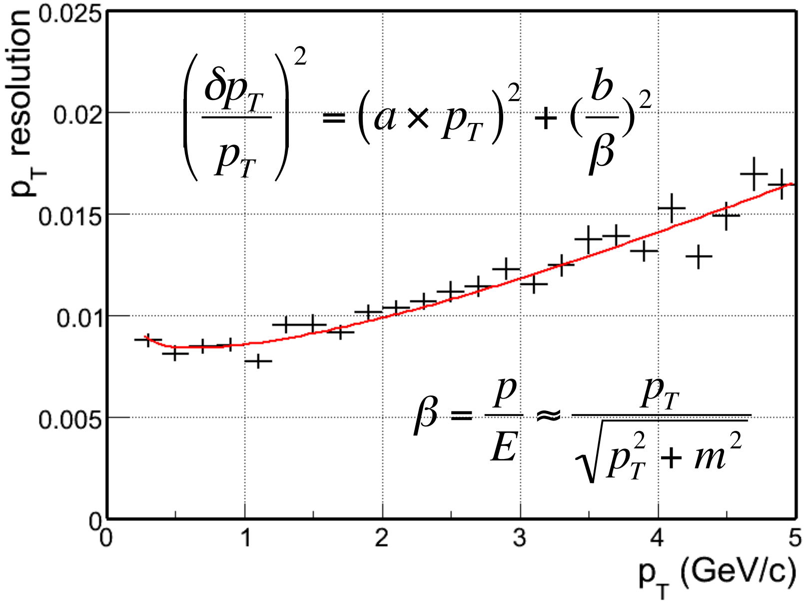
P. Huovinen and P. Petreczky, NPA837 (2010) 26.



Higher energy =>
larger initial temperature
longer evolution time.

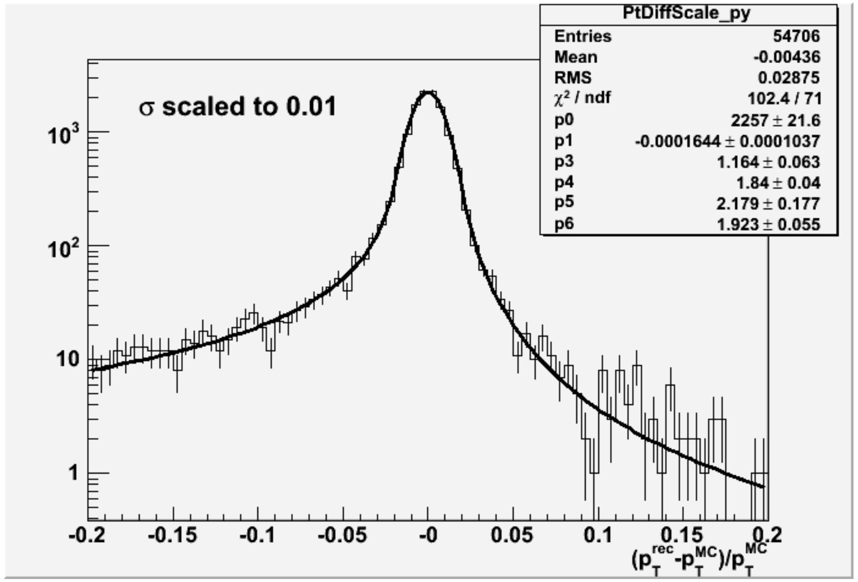
Detector acceptance and response





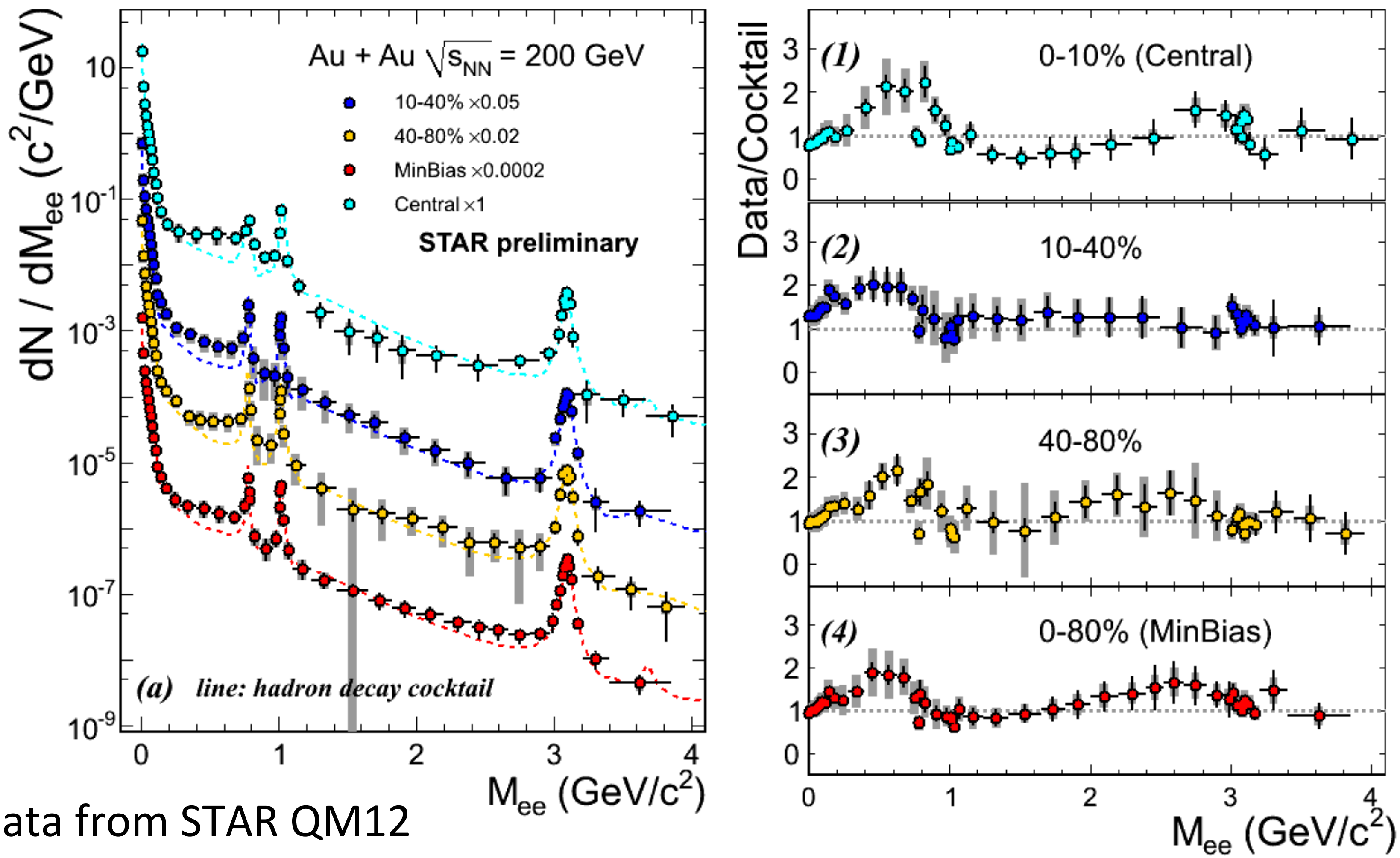
To compare the calculation with measurement, we have to also consider:

- Detector acceptance
- Mass/momentum resolution
- Electron bremsstrahlung.



Double-crystal-ball function for energy loss

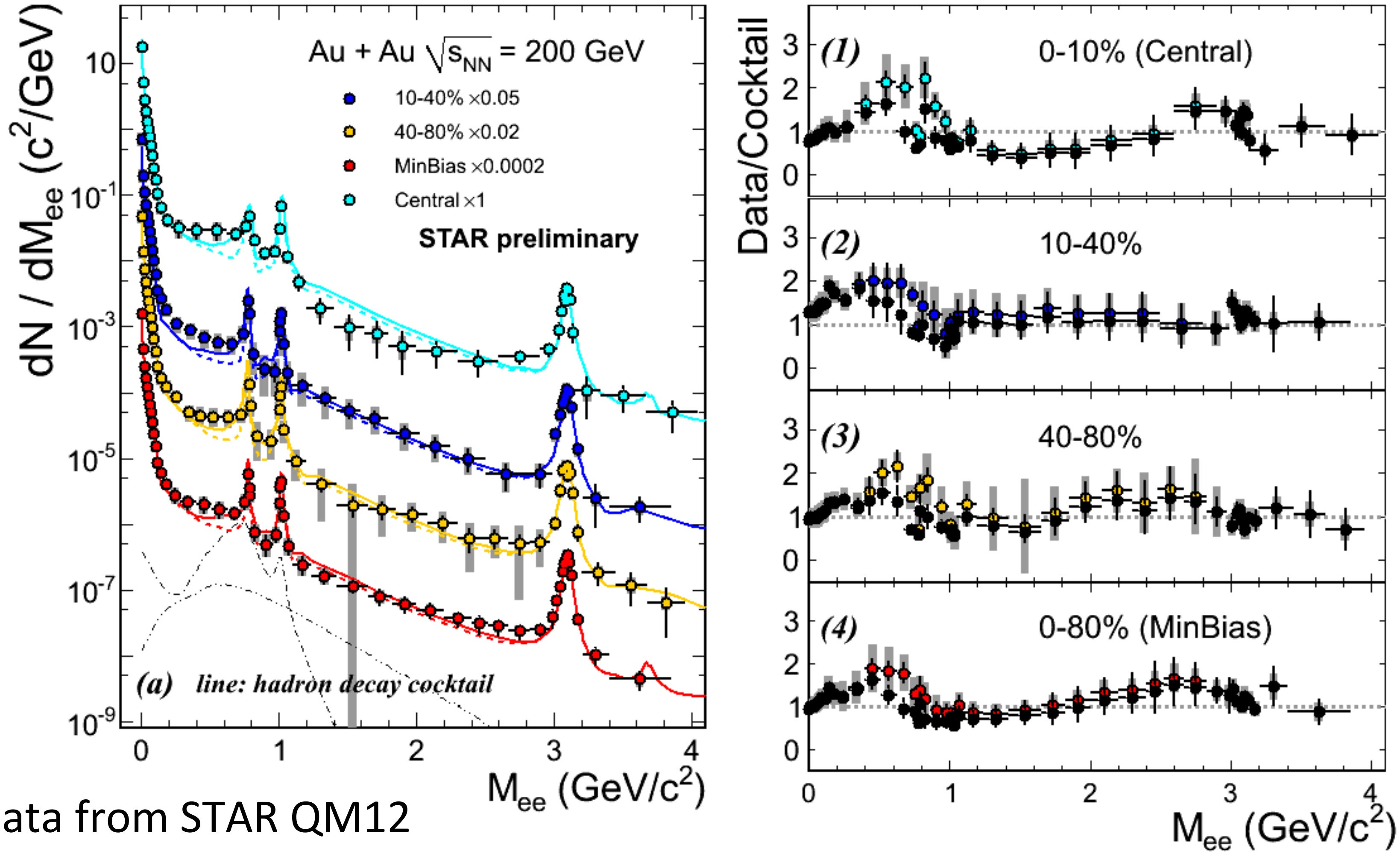
Di-electron production in Au+Au 200 GeV



Data from STAR QM12

- ✧ LMR Enhancement compare with cocktail w/o ρ. Weak centrality dependence.
- ✧ In-medium ρ plays important role, data over cocktail w/ ρ are more close to 1.

Di-electron production in Au+Au 200 GeV



Data from STAR QM12

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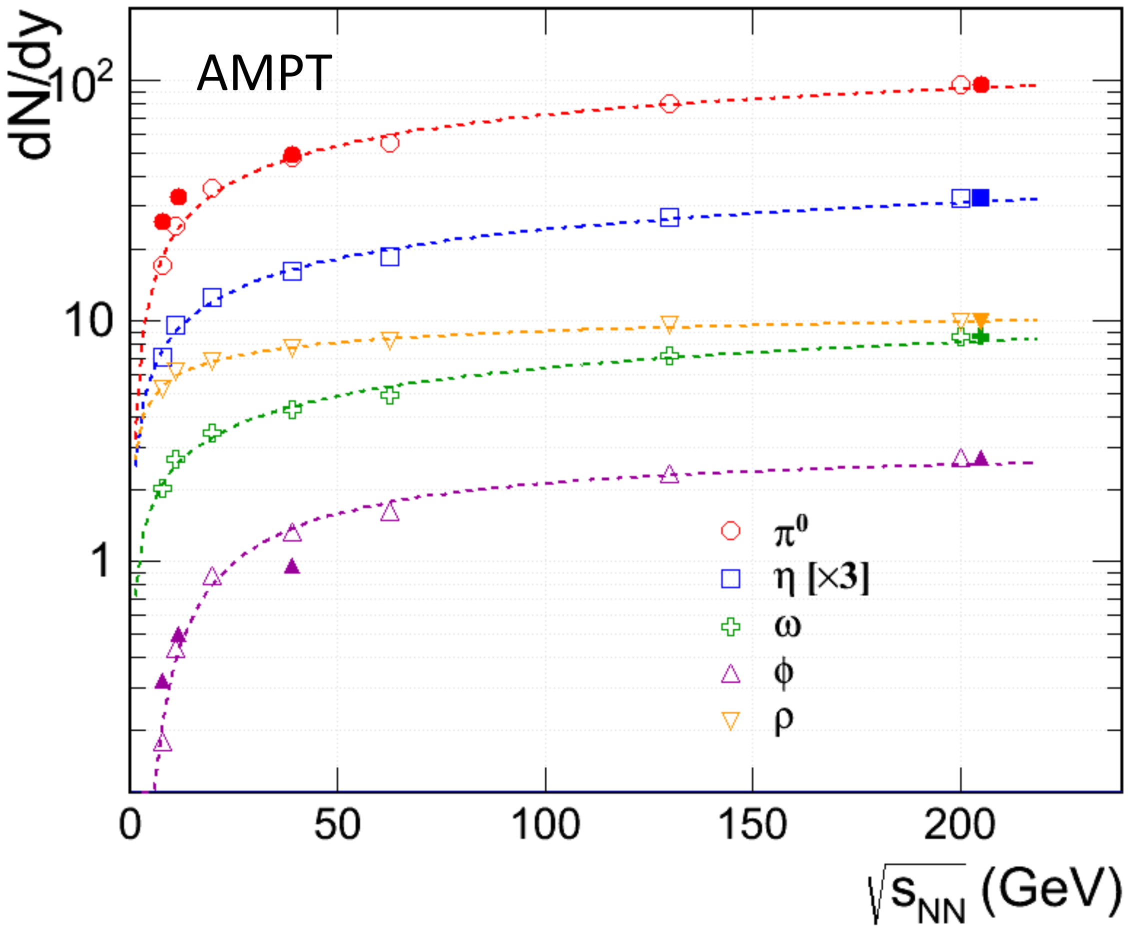
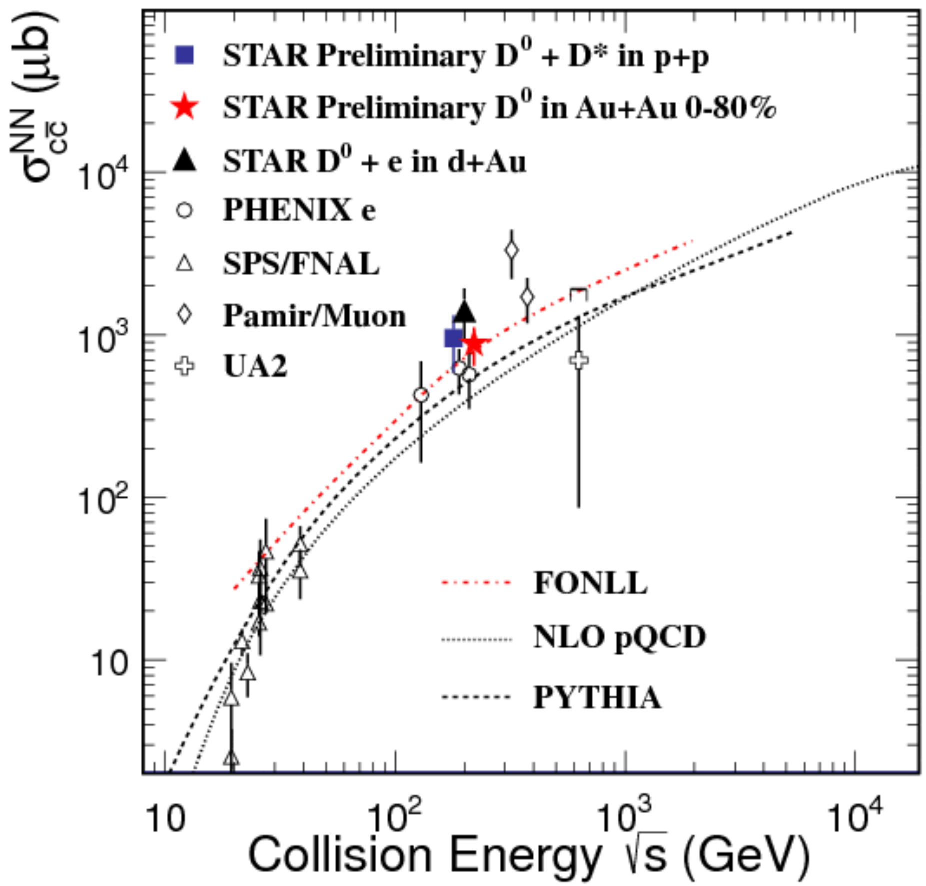
Extrapolation to lower energies

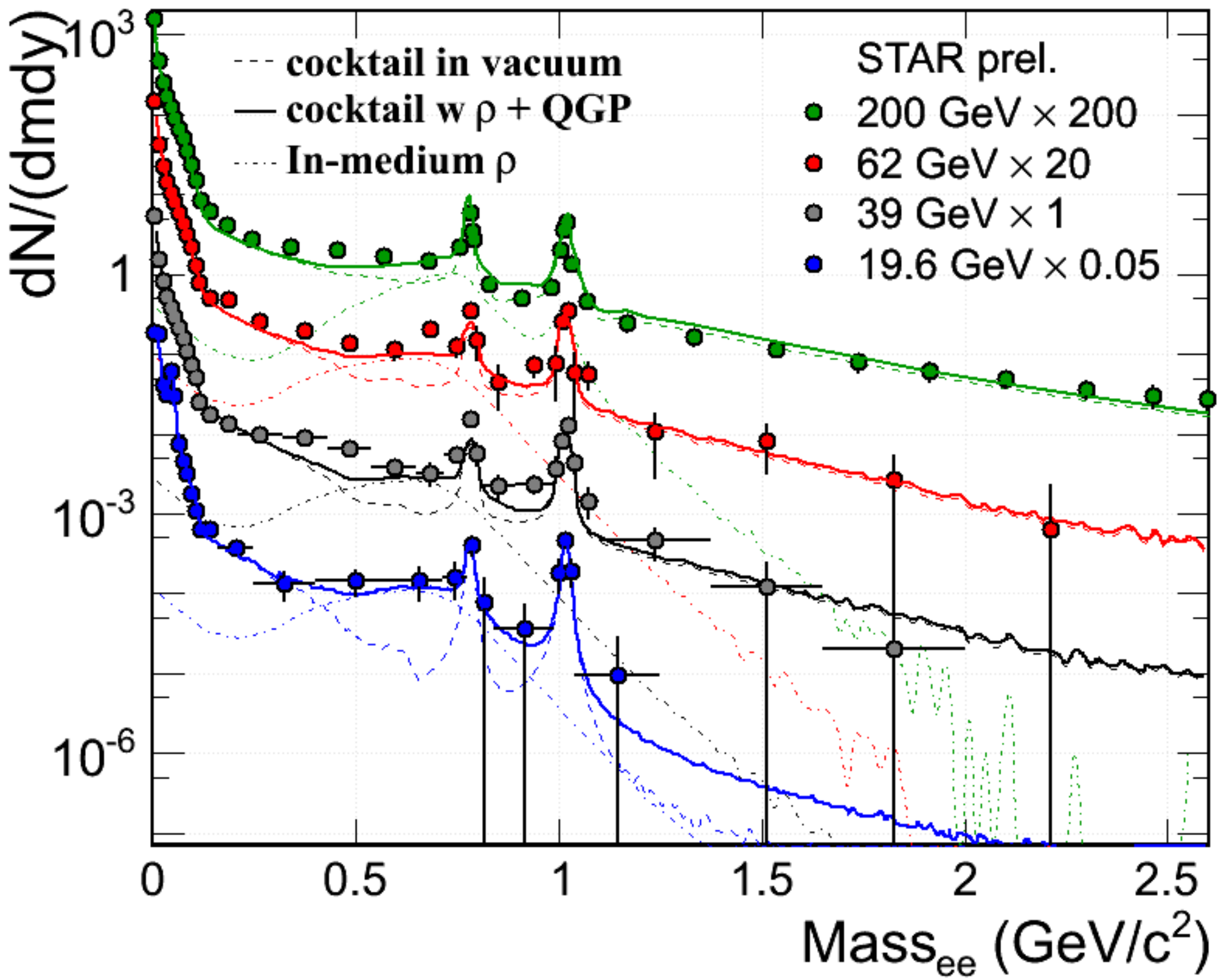
dN/dy and p_T distributions from AMPT calculations.
Charm cross section: NLO calculation for low energies.





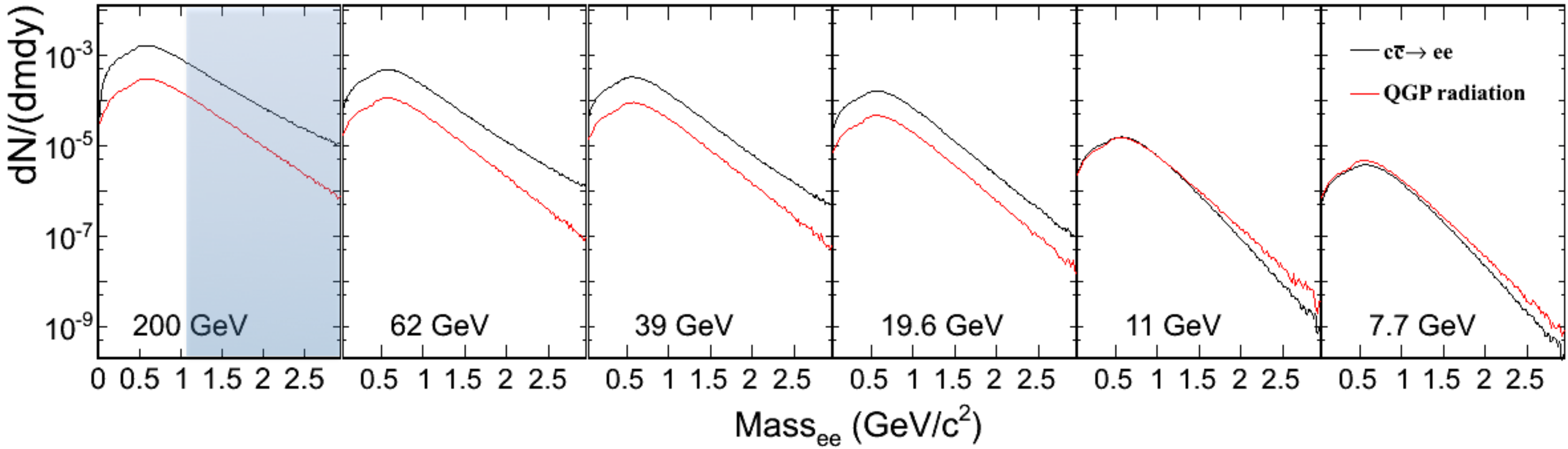
Scale to measurements at 200 GeV (solid symbols), some difference at lower energy.

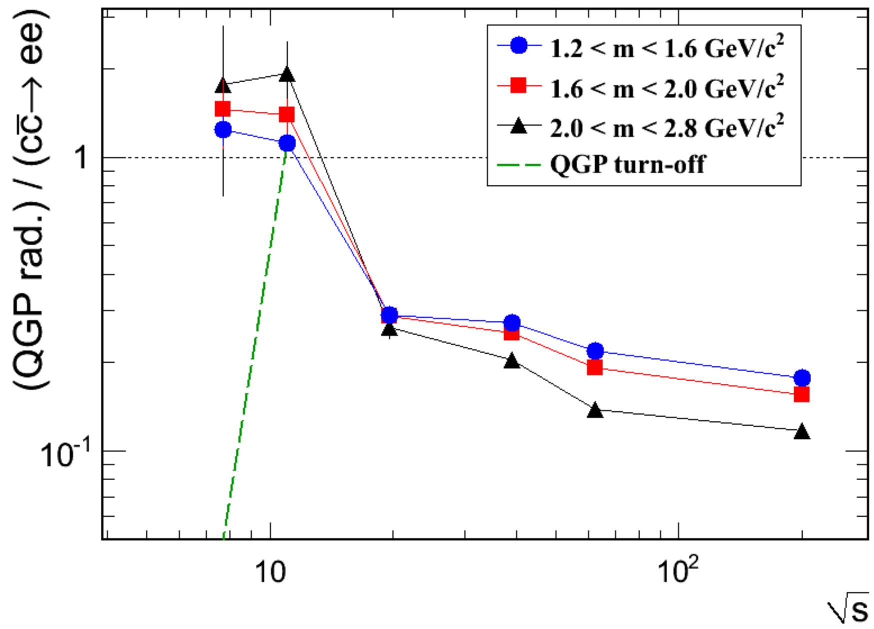
Di-lepton production at lower energies



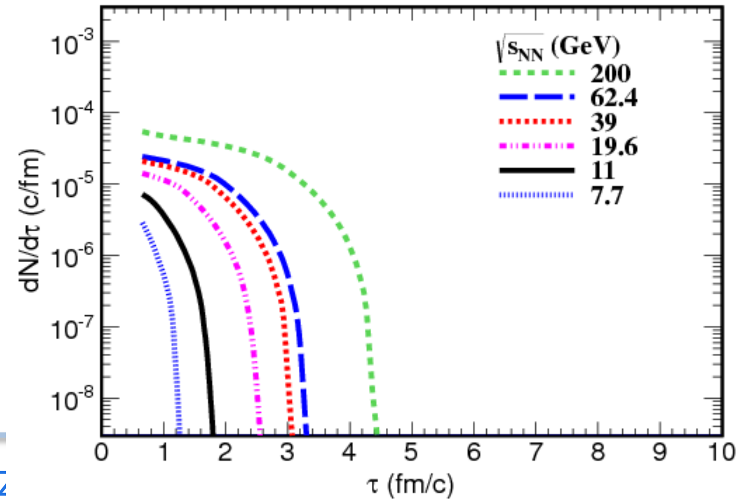
- RHIC BES Program: explore LMR down to SPS energy.
- Observed low-mass enhancement in all energies.
- In-medium ρ w/ finite baryon density describe LMR enhancement well.

IMR signal / background

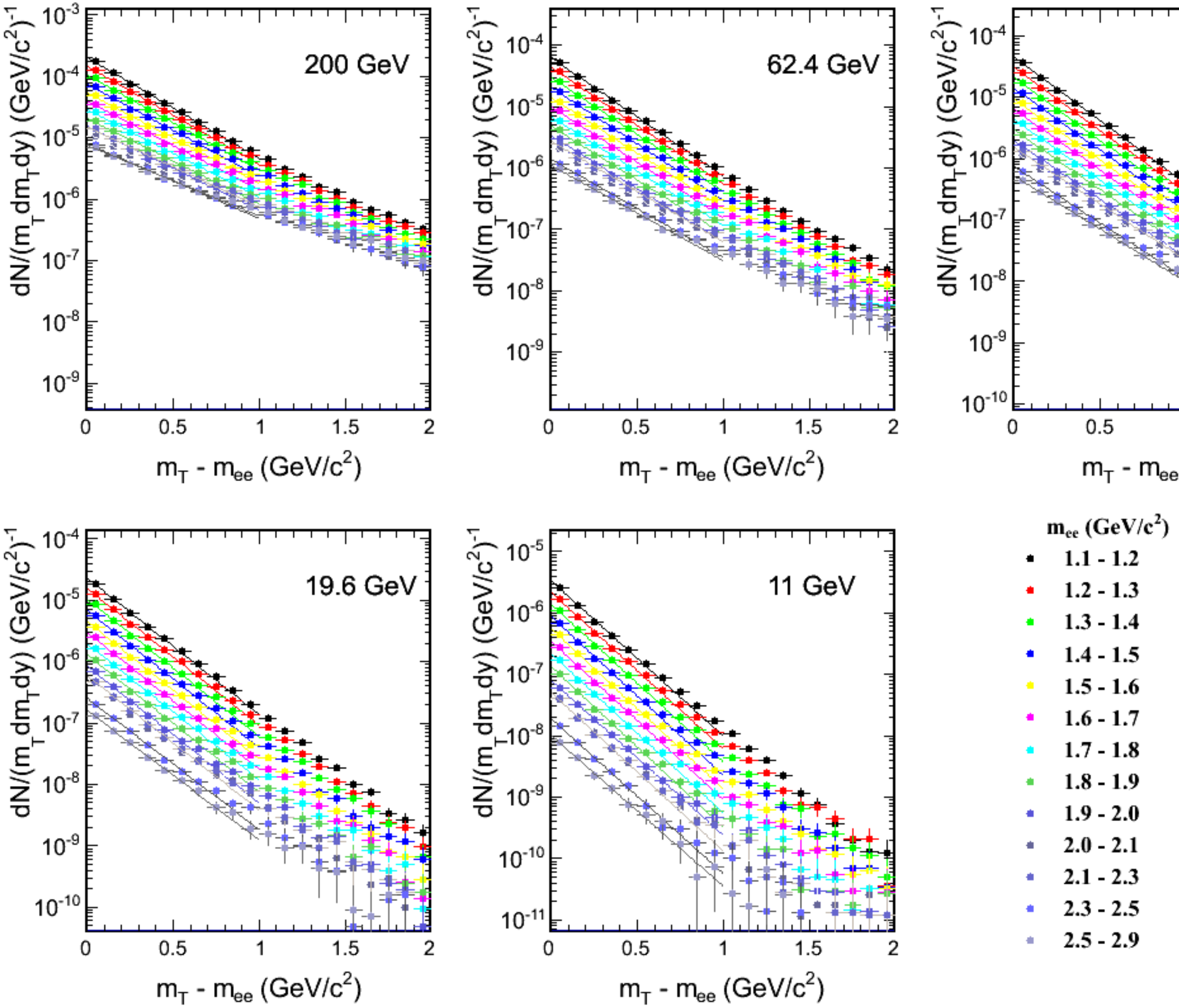




- ✧ Signal / b.g. ratio is ~ a few percent in higher energies.
- ✧ Signal enhanced in lower energy, relative large emission rate even for a short-lived QGP system.
- ✧ Test possible phase transition.



m_T slope of in the IMR

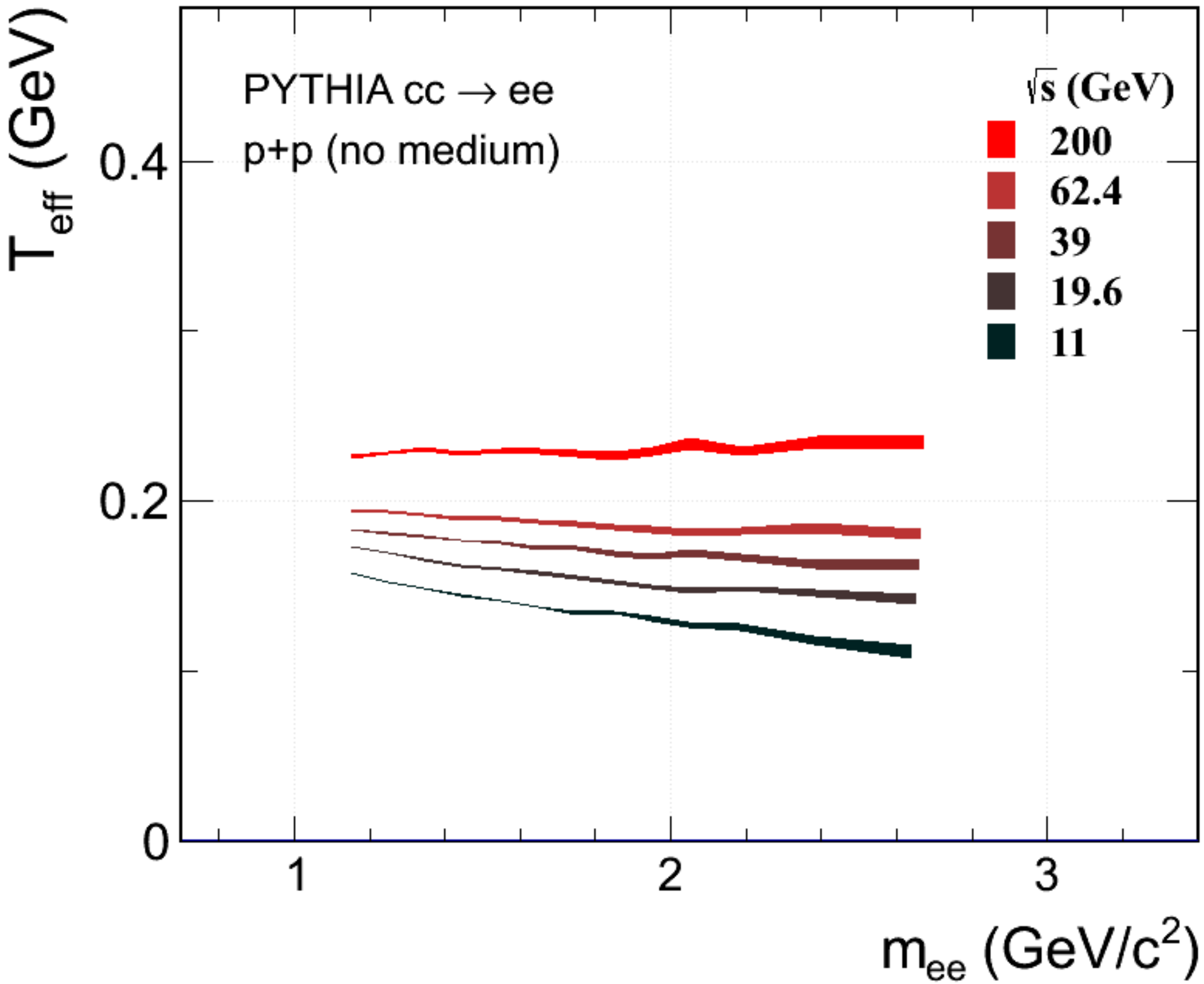


PYTHIA simulation:
correlated charm at BES energies.

Random Phase-space:
assuming decay daughters azimuth randomly washed out.

Thermal:
2+1D ideal hydro
H. Xu, Q. Wang (priv. comm).
H. Xu, *et al.*, PRC 85 024906 (2012).

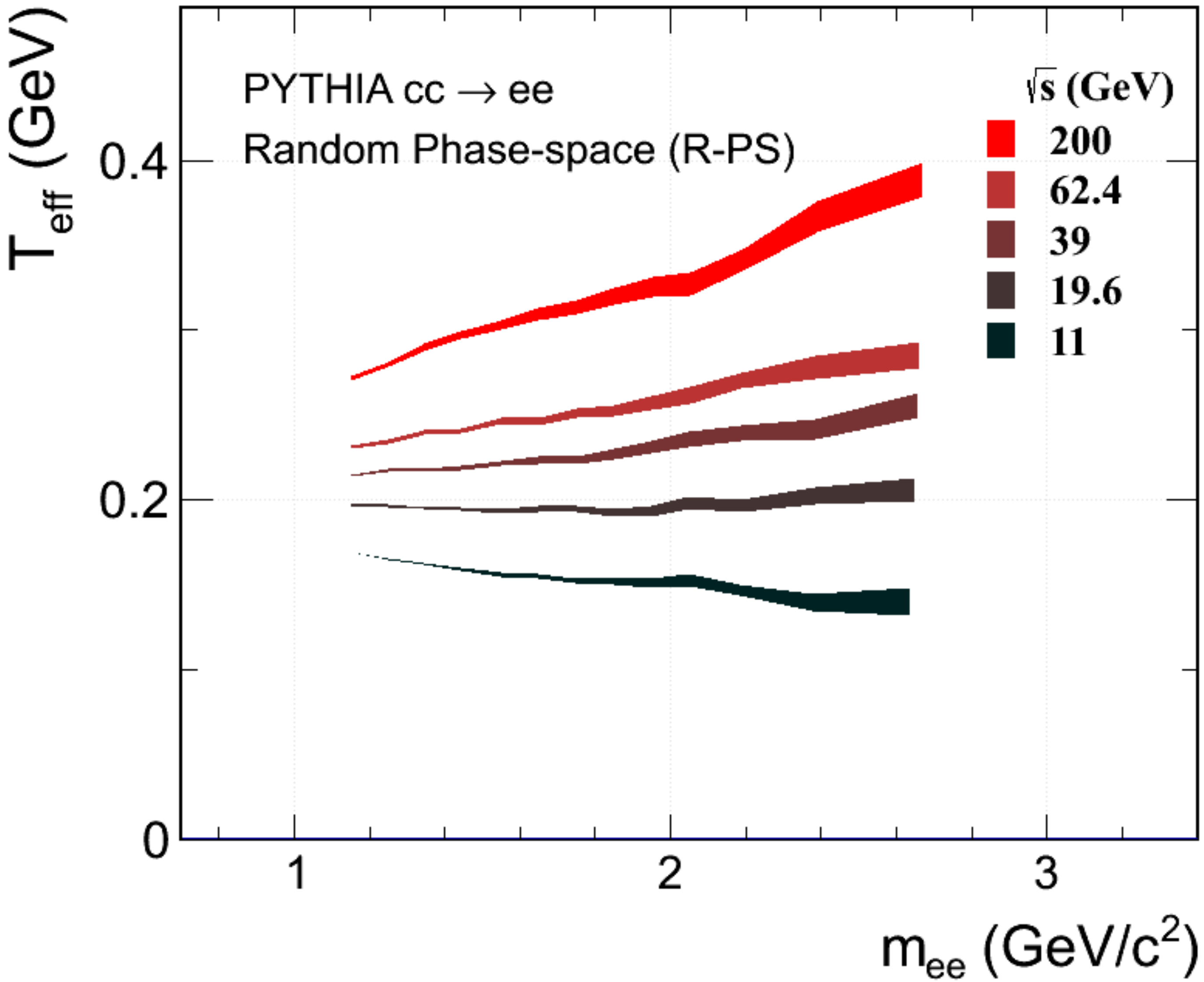
m_T slope of in the IMR



Y. Zhang CPOD2011

p+p from PYTHIA always shows decreasing vs. mass.

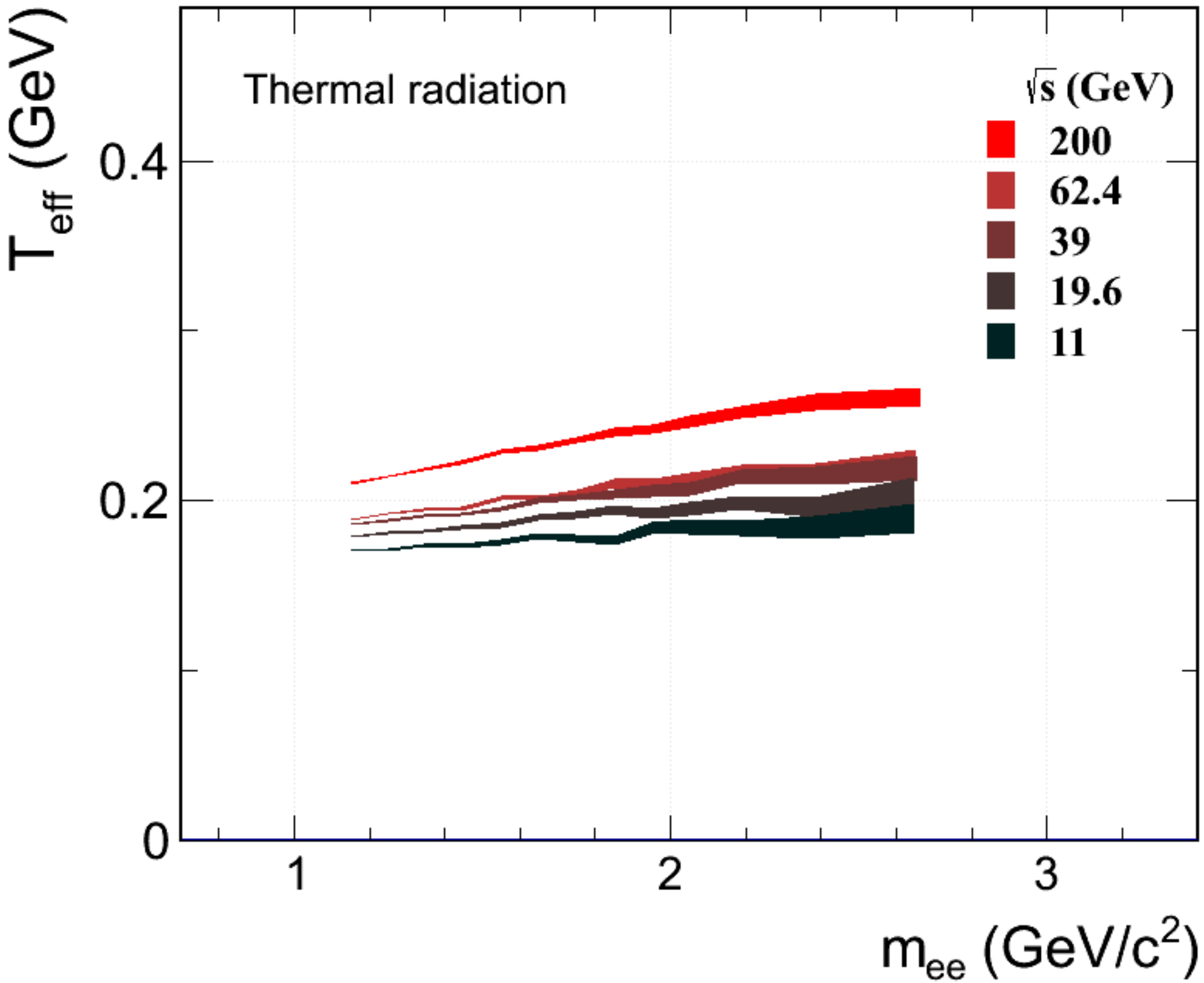
m_T slope of in the IMR



Y. Zhang CPOD2011

Assuming the angular correlation of the decay products is totally washed out in the medium, it gives much larger temperature and stronger energy dependence.

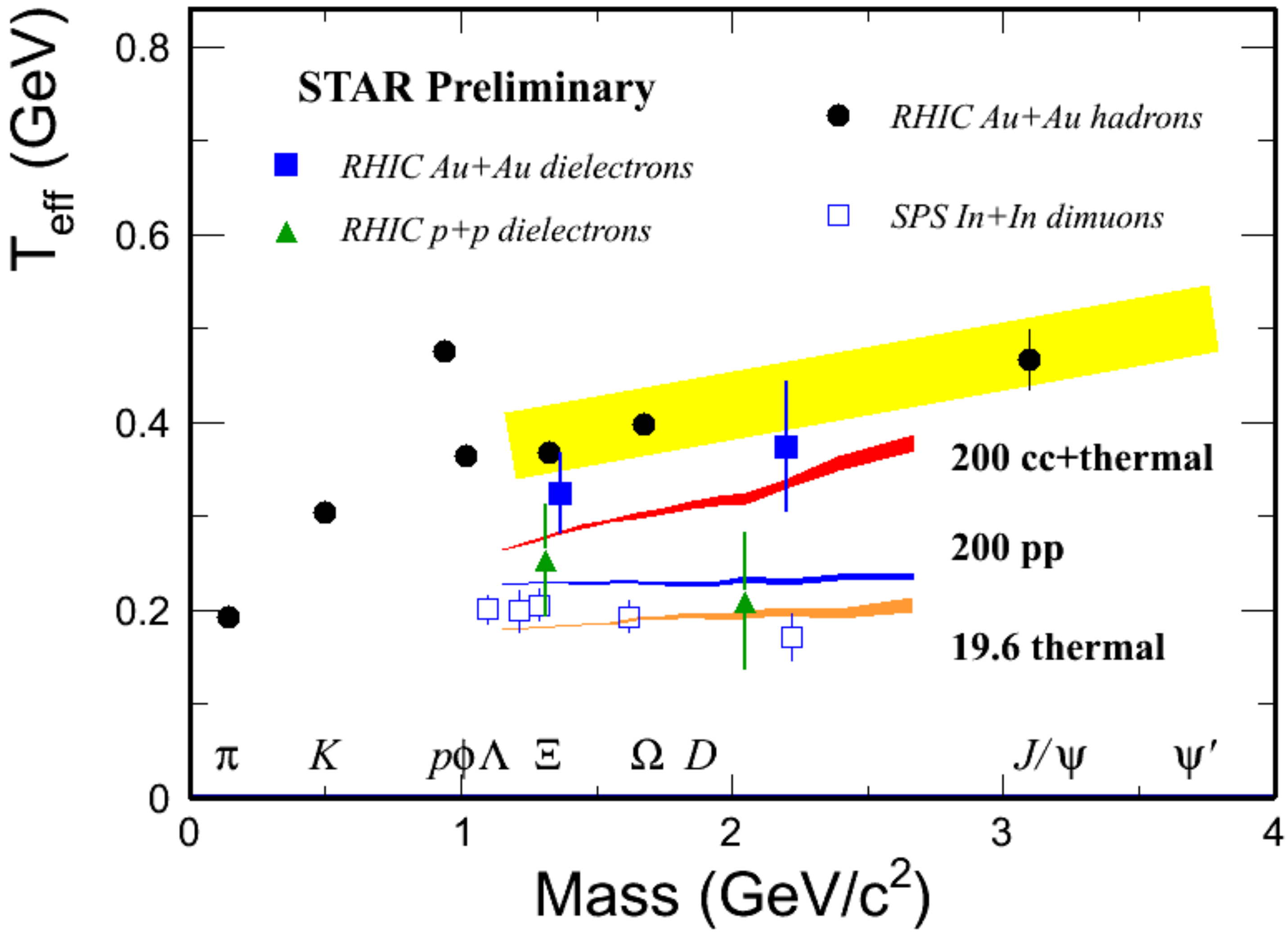
m_T slope of in the IMR



Y. Zhang CPOD2011

2+1D hydrodynamics gives weaker energy dependence, but always increases vs. mass.

m_T slope of in the IMR



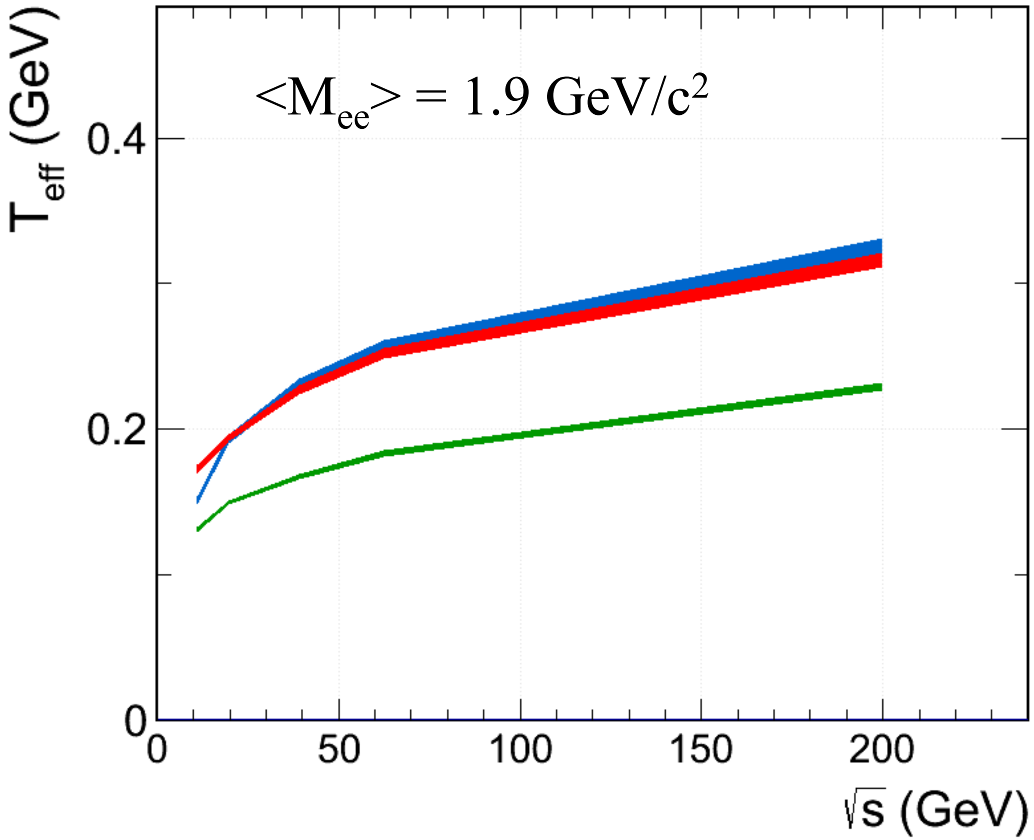
Y. Zhang CPOD2011

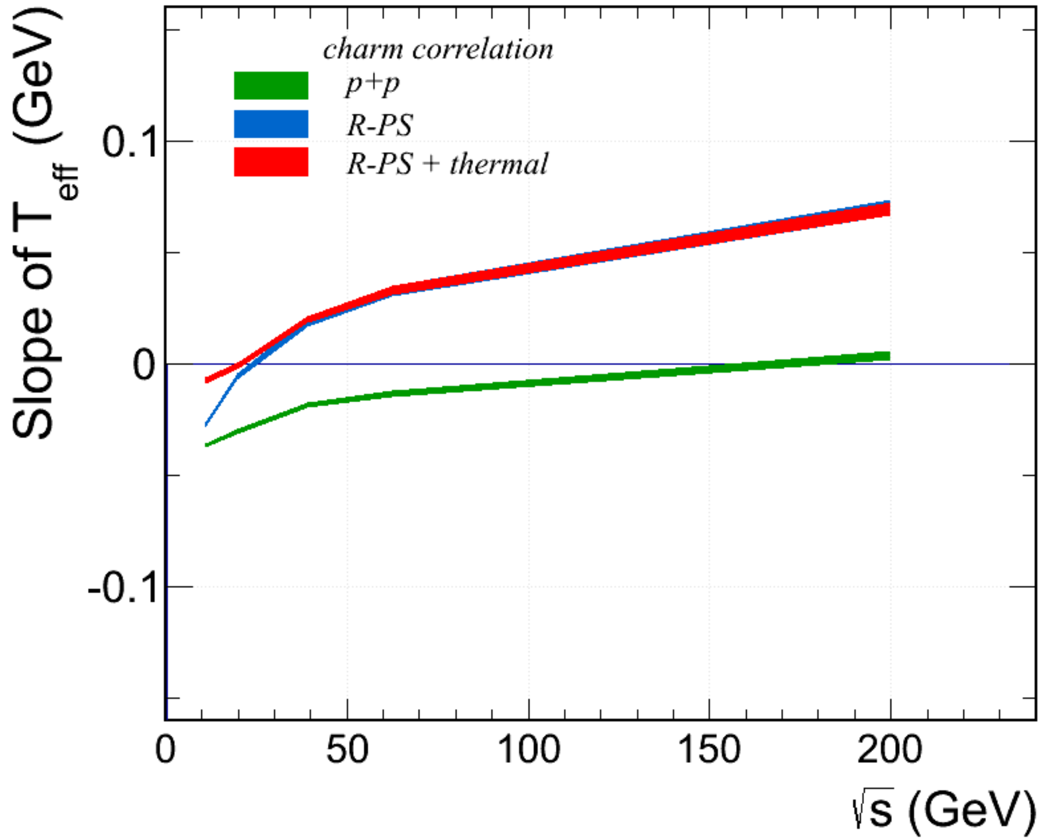
Within errors 19.6 GeV agrees with NA60 (~17 GeV), seems opposite trend.

Charm correlation in p+p is consistent with STAR p+p data (QM11).

Charm correlation modified by medium. Thermal + charm reproduce STAR Au+Au data well.

Possible observation at phase transition?



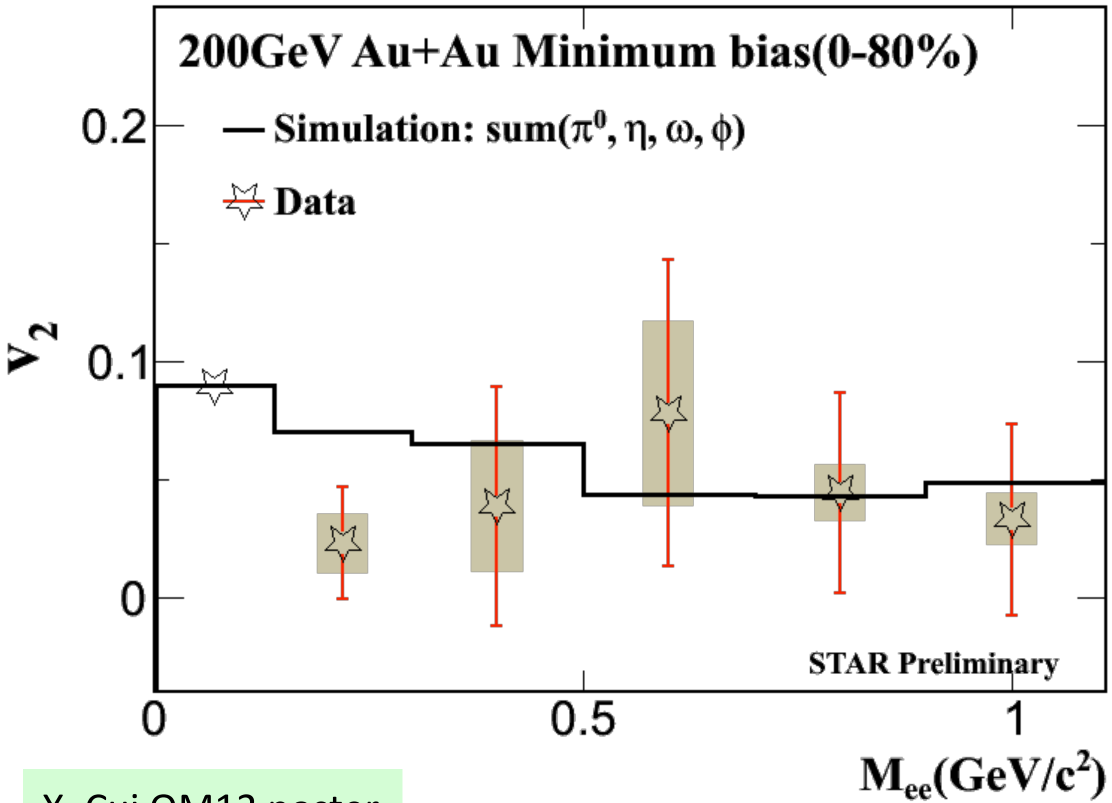


High energy dominant by charm correlation, lower energy charm and thermal contributions are comparable.

Both T_{eff} and its slope in medium are significant higher than the system w/o medium.

Phase transition could happen if the T_{eff} increases dramatically or the sign of its slope changes from negative to positive.

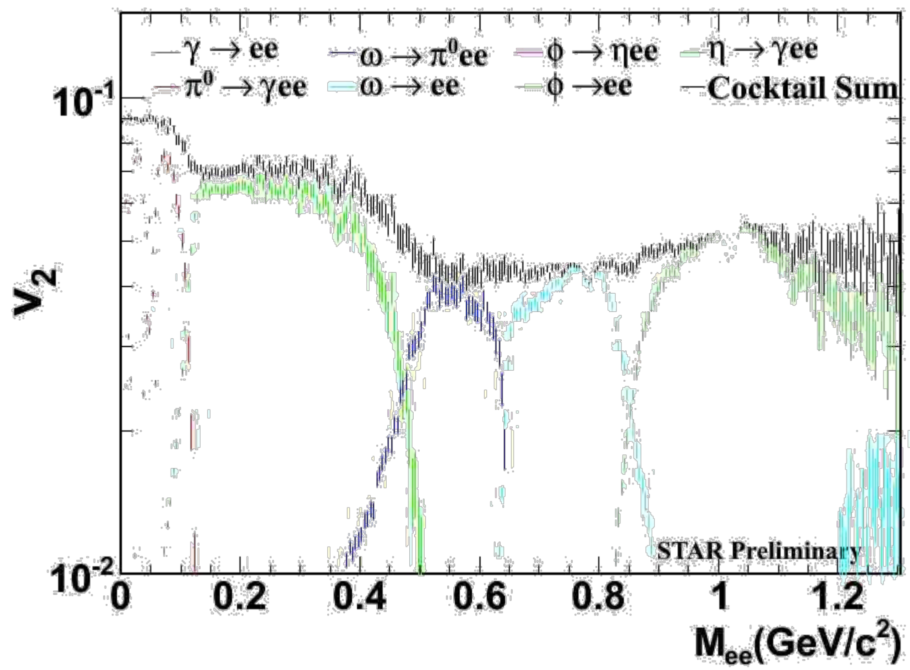
Di-electron v_2 in Au+Au 200 GeV



X. Cui QM12 poster

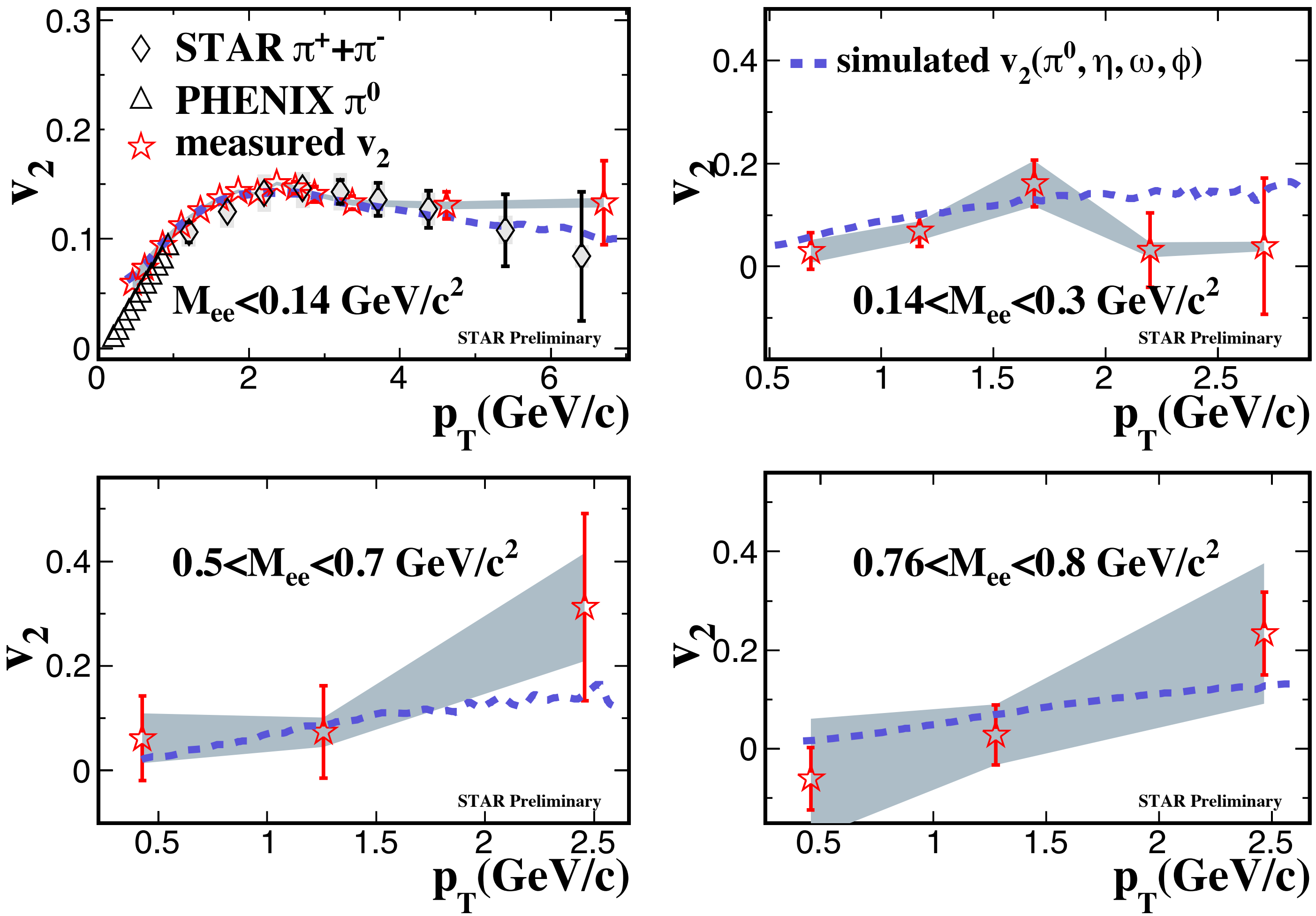
- First measurement from STAR.
- TPC event-plane method.
- Consistent with cocktail simulation with mesons decay in vacuum.

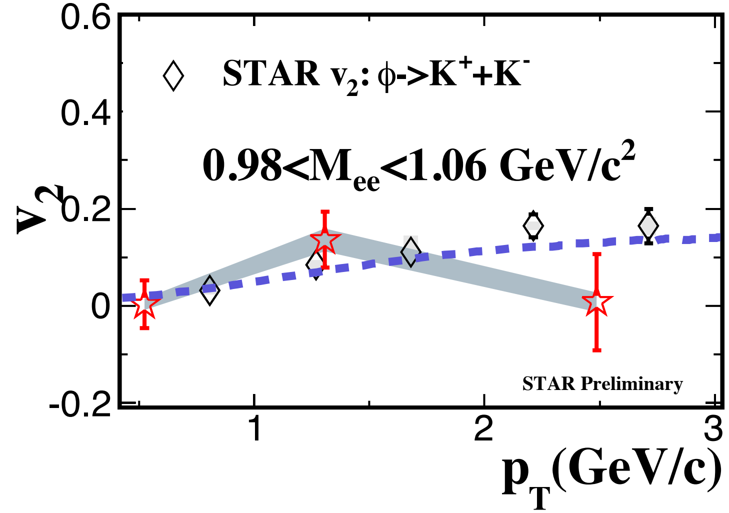
Current precision does not allow to study medium modification.



Di-electron v_2 p_T dependence

Au+Au $\sqrt{s_{NN}}$= 200GeV 0-80% centrality





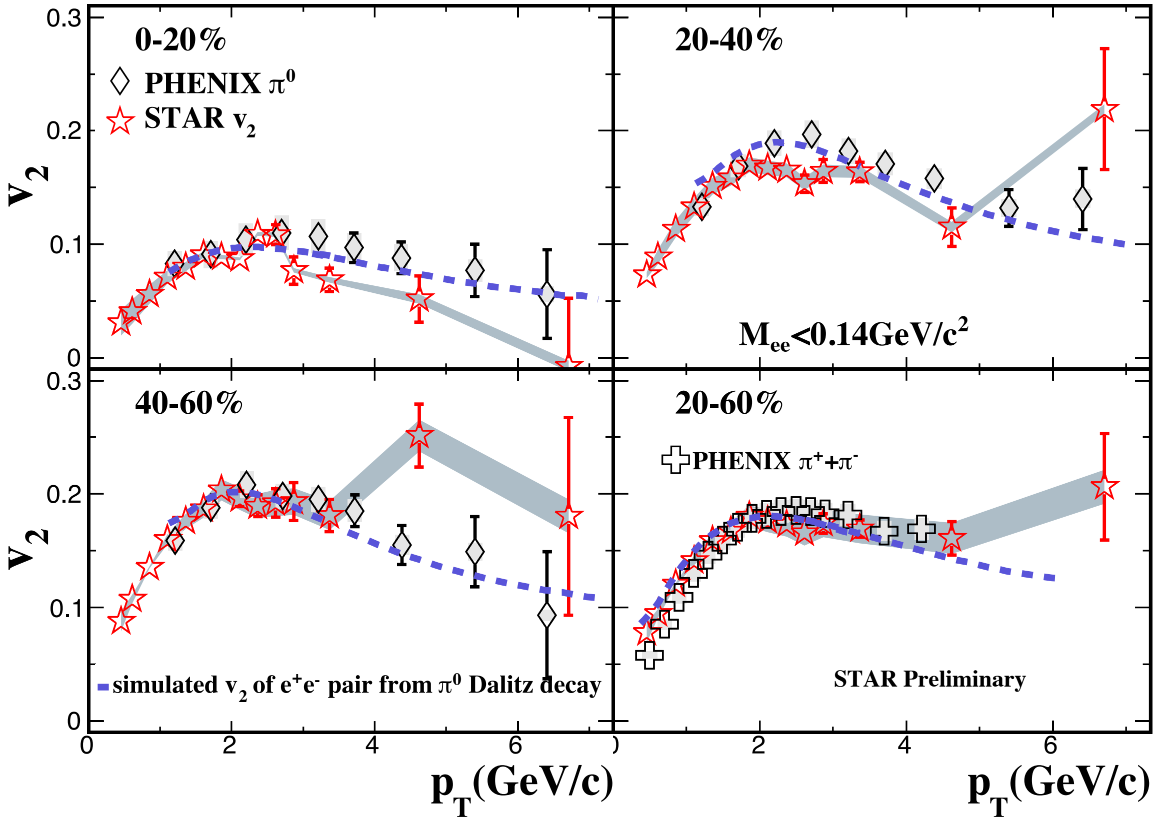
M < 0.14 GeV/c^2
Consistent with measured $\pi^{\pm}$ (STAR) and π^0 (PHENIX) at high p_T.
Good tool to measure high p_T π^0

M ~ ρ (0.14 – 0.8 GeV/c^2)
Need more data to study medium modification.

M ~ ϕ (0.98 – 1.06 GeV/c^2)
Consistent with hadronic decay channel.
ϕ seems not dominant by KK->ϕ, need more data to confirm

- $v_2(p_T)$ consistent with simulations & measurements

Di-electron v_2 centrality dependence



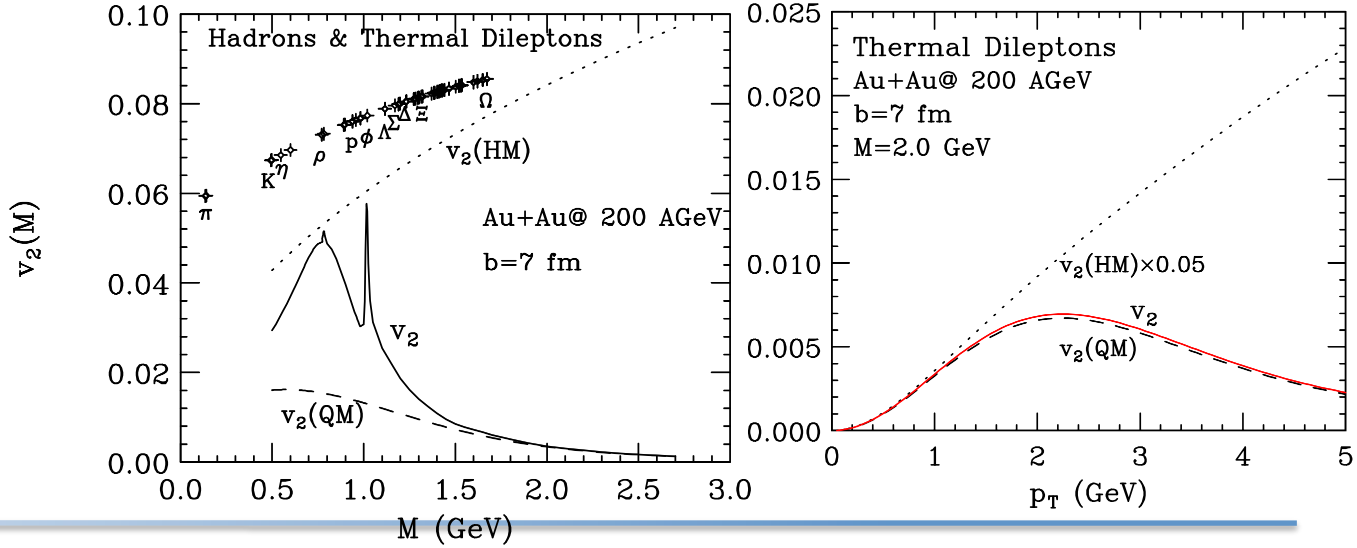
LMR: hadronic process dominant
To distinguish hadronic/partonic contributions need extend this measurement to IMR.

Need detector upgrades:
- HFT => Reject long life-time decays, determine correlated charm
- MTD => e+μ correlation, IMR di-μ measurement.

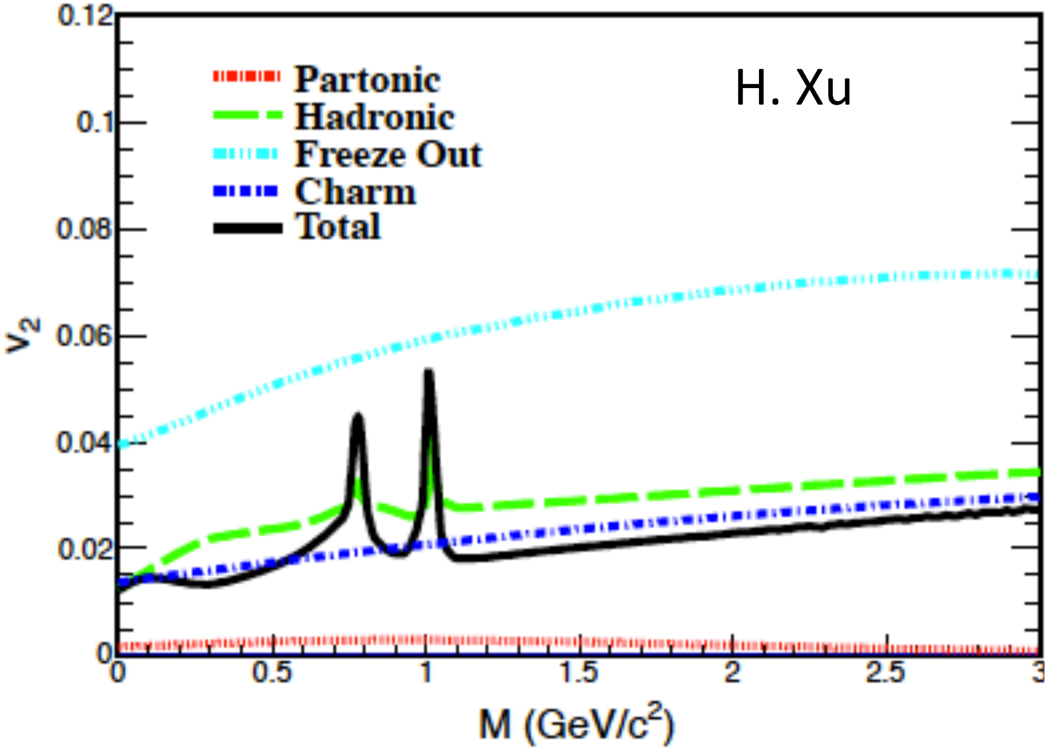
Centrality dependence $v_2(p_T)$

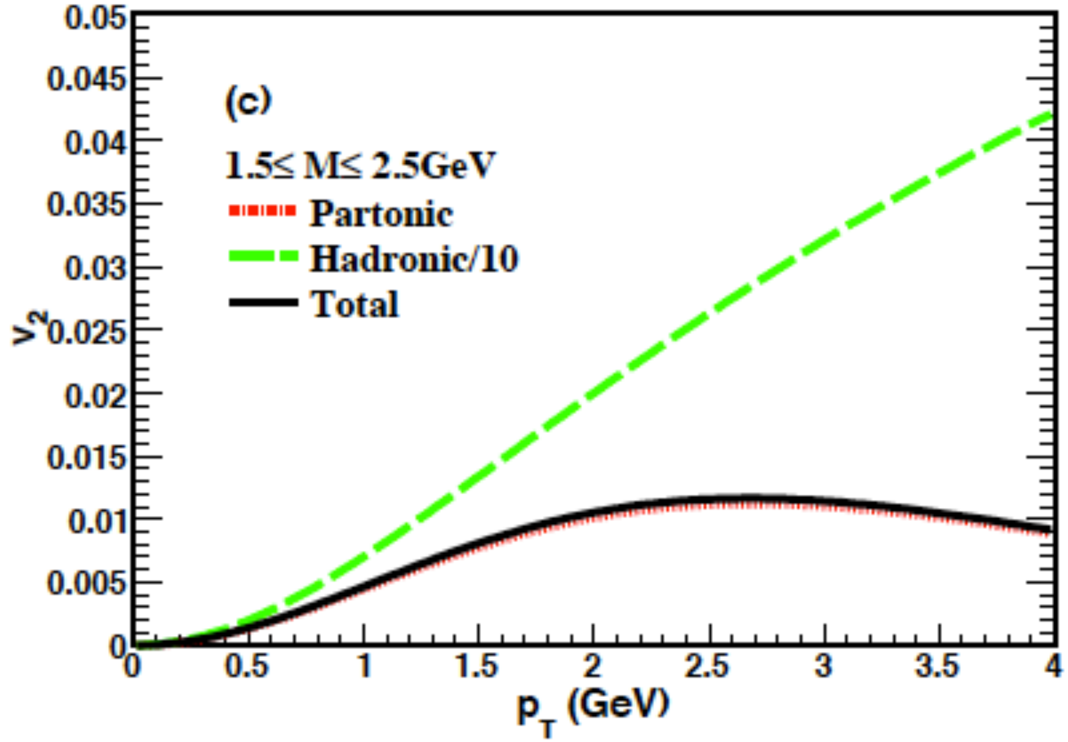
M_{ee}<0.14 GeV/c^2 (π^0)

- consistent with simulations
- consistent with measurements

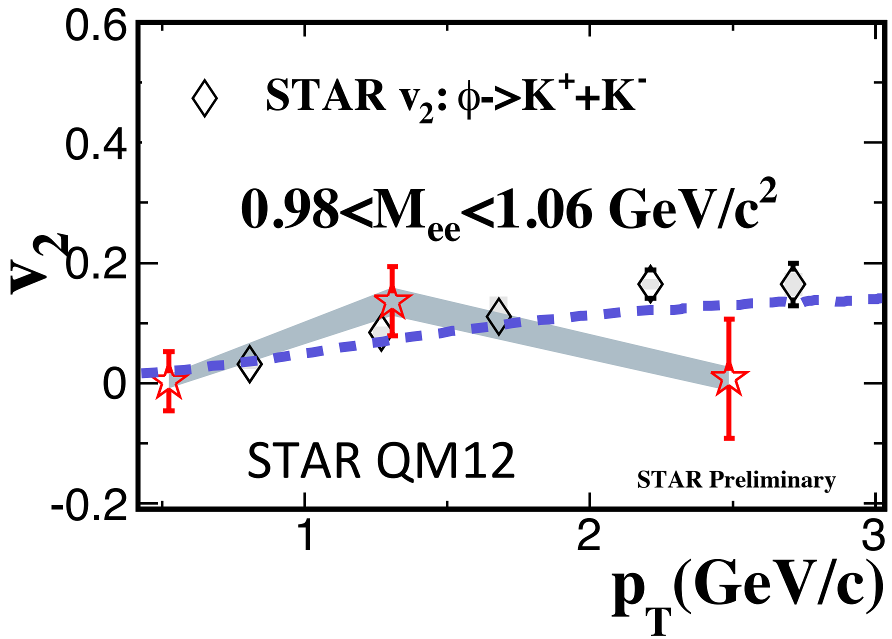


Di-electron v_2





- Sensitivity to separate hadronic/partonic.
- Experimental data M_{ee} < ~ 1 GeV/c, expecting more statistics + upgrade for IMR and high p_T.



Summary

- Experimental data shows LMR enhancement compared with vacuum cocktails.

  - In-medium ρ broadening explains the enhancement reasonably for each RHIC BES energies from 19.6 to 200 GeV.

- IMR QGP radiative signals may enhanced over correlated charm background in lower energy.

  - Future detector upgrades will also help for background suppression.

  - May be sensitive to the possible phase transition.

- IMR slope with naïve assumption seems agree with data reasonably for both SPS and RHIC energies.

- Di-lepton v_2 is ideal probe for distinguish partonic/hadronic processes.

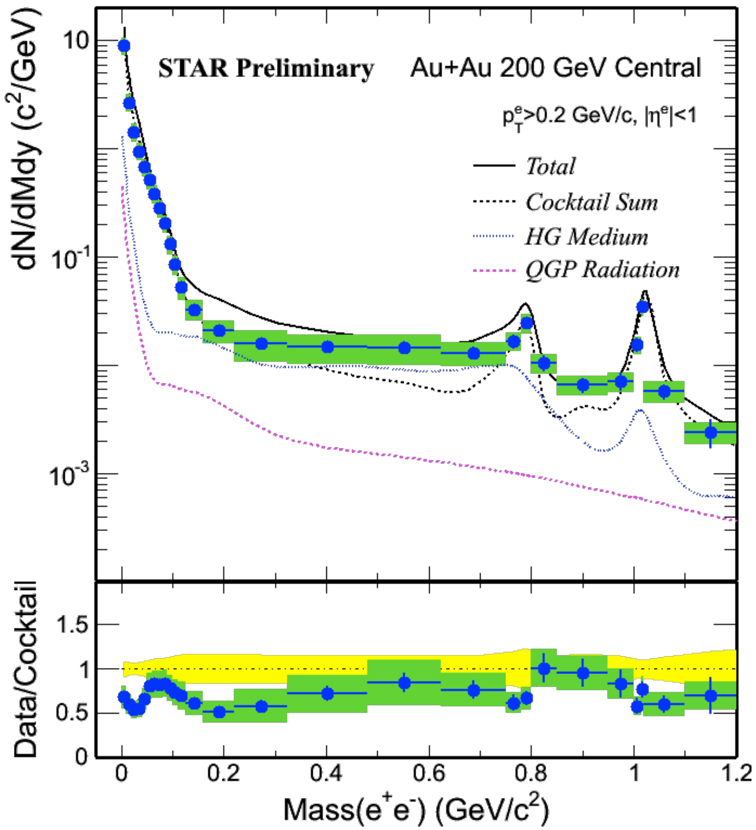
  - High sensitivity at IMR and large p_T.

  - Need future experimental data for comparison.

Looking forward to BES Phase-II and increasing luminosity of RHIC runs.

Backup Slides

LMR compare with models (I)



Ralf Rapp (priv. comm.)

R. Rapp, Phys.Rev. C 63 (2001) 054907

R. Rapp & J. Wambach, EPJ A 6 (1999) 415

Complete evolution:

Cocktail (in vacuum) + HG + QGP =>

- ρ "melts" when extrapolated close to phase transition boundary.
- agreement w/in uncertainties.

H. Xu, Q. Wang (priv. comm.)

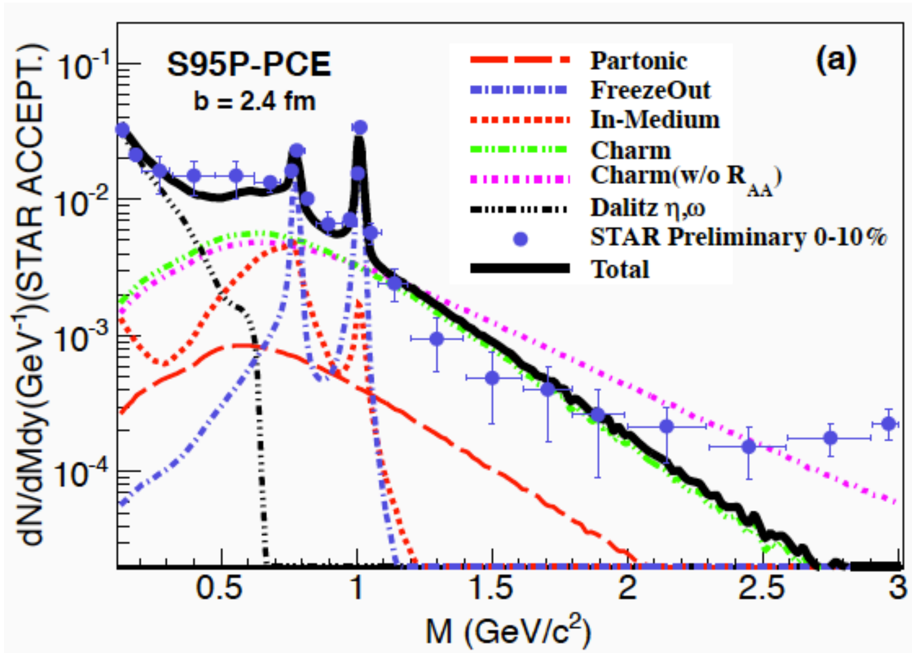
H. Xu, *et al.*, Phys. Rev. C 85 024906 (2012).

In-medium ρ: Multi-body effective theory

Partonic (QGP): 2+1D ideal hydro

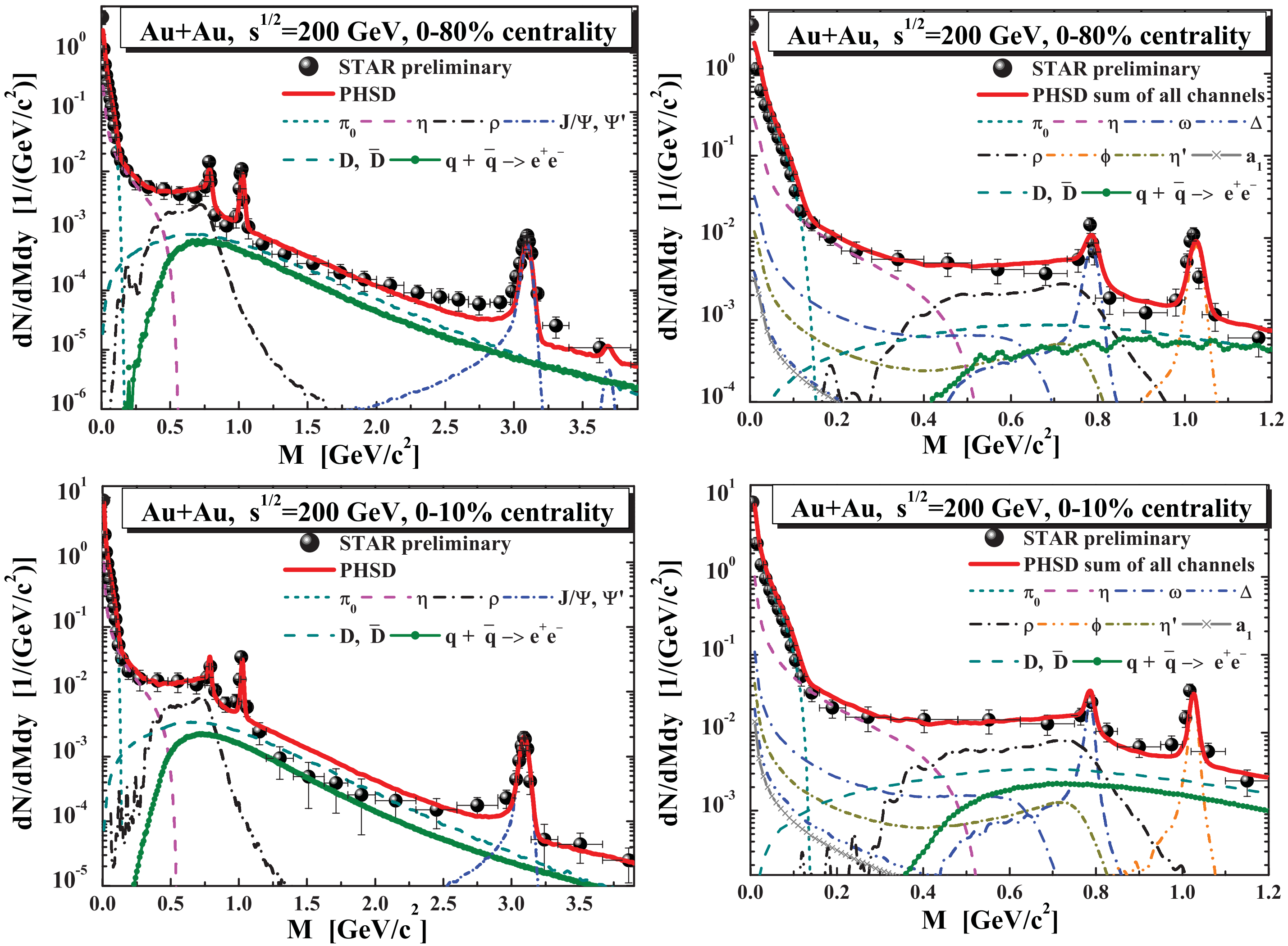
FreezeOut + IM + QGP =>

- agree w/in uncertainties.



LMR compare with models (II)

O. Linnyk et al., Phys. Rev. C 85 024910 (2012)



Parton-Hadron String-Dynamics

1. Collisional broadening of vector mesons
2. Radiation from QGP

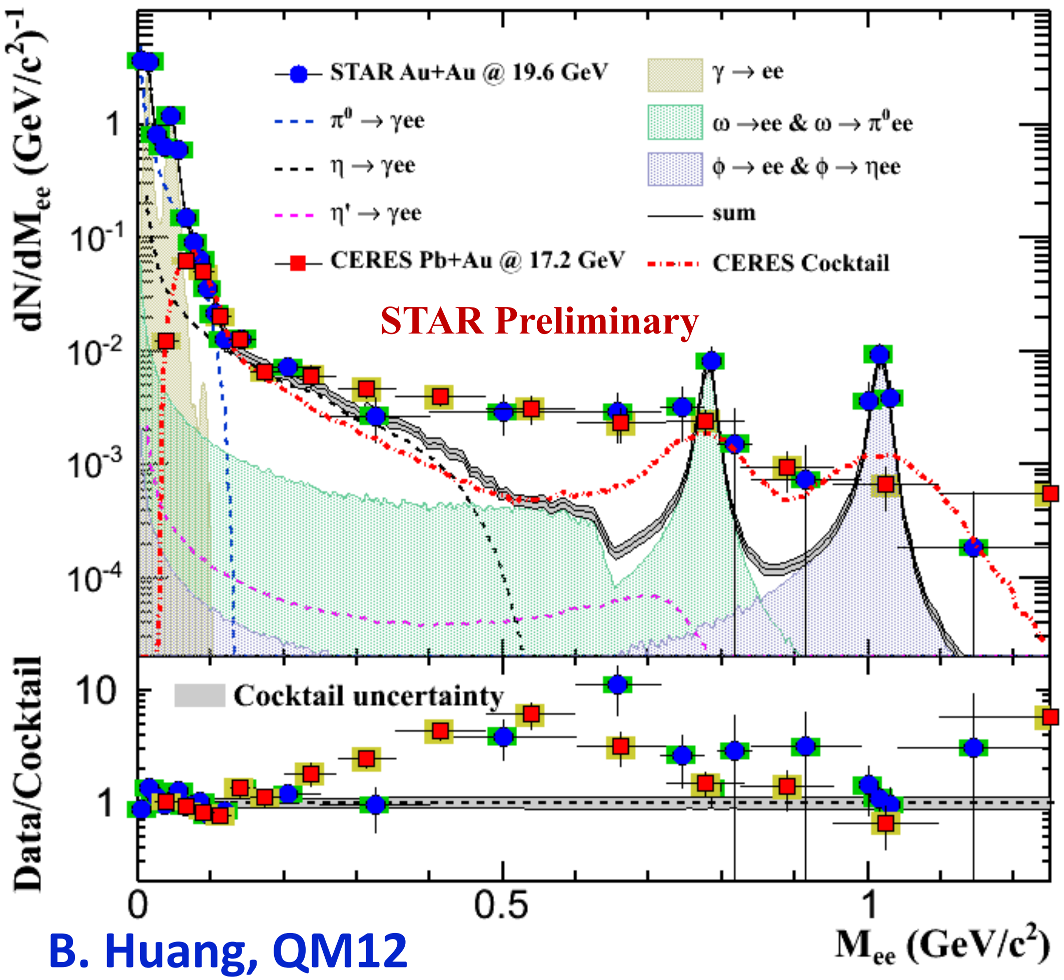
Minimum bias collisions (0-80%):

- Generally good agreement

Central collisions (0-10%):

- PHSD roughly in line with LMR region
- Similar as STAR cocktail, overshot IMR.

Compare with SPS energy



B. Huang, QM12

Enhancement factor	$0.2<M_{ee}<0.6$ GeV/c^2
STAR	1.9 ± 0.6± 0.4
CERES	2.73 ± 0.25±0.65±0.82[decays]

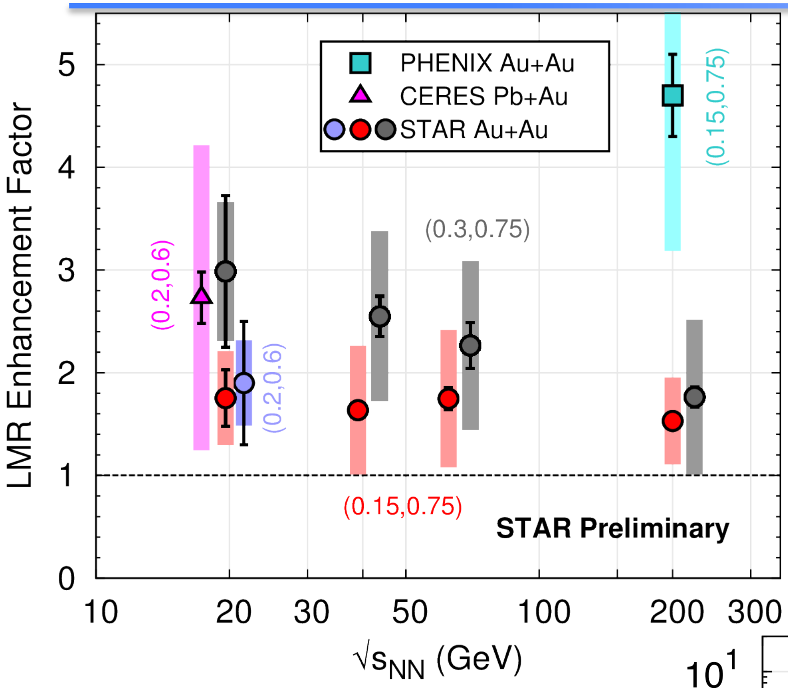
- π yield is from STAR π^{+-} measurement, other meson yields derived from SPS meson/π^0 ratio.

➢ Different centrality & acceptance:
  - STAR Au+Au:
    0-80% centrality
    p_T>0.2 GeV/c, $|\eta|<1$, $|y_{ee}|<1$.
  - CERES Pb+Au:
    0-28% centrality.
    p_T>0.2 GeV/c, $2.1<\eta<2.65$, θ_{ee}>35mrad.

➢ Different detector resolution.

Low mass enhancement comparable to CERES w/in uncertainties.

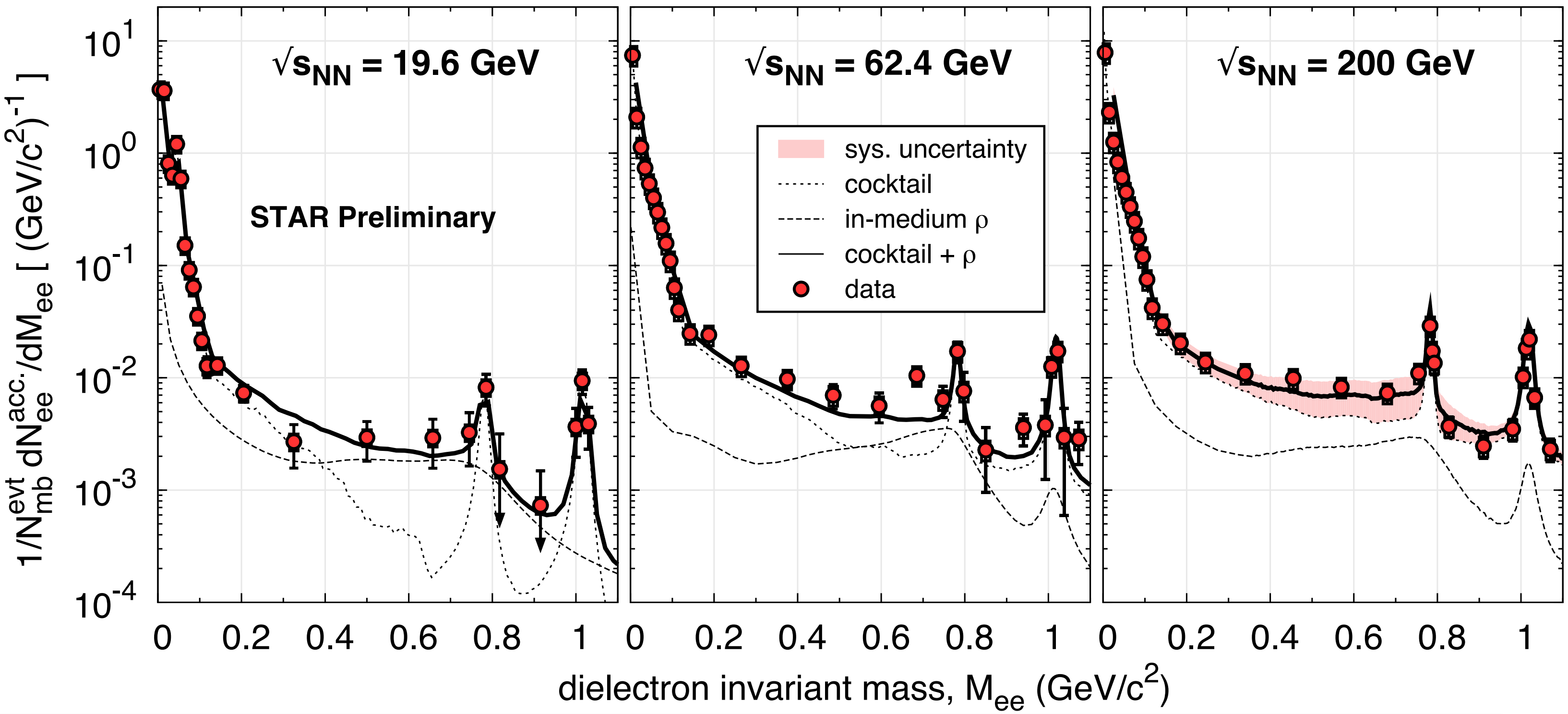
LMR enhancement vs. collision energies



- LMR enhancement factor shows no significant energy dependence from 19.6 to 200 GeV.
- Theoretical calculations of in-medium ρ broadening with total baryon density from 19.6-200 GeV reproduce LMR excesses.

by Ralf Rapp (priv. comm.)

Adv. Nucl.Phys. 25, 1 (2000)
arXiv:nucl-th/0204003v1



In-vacuum rho line shape

$$\frac{dN}{dm_{ee}dp_T} \propto \frac{m_{ee}M_\rho\Gamma_{ee}}{(M_\rho^2 - m_{ee}^2)^2 + M_\rho^2(\Gamma_{\pi\pi} + \Gamma_{ee}\Gamma_2)^2} \times PS,$$

ρ line shape:

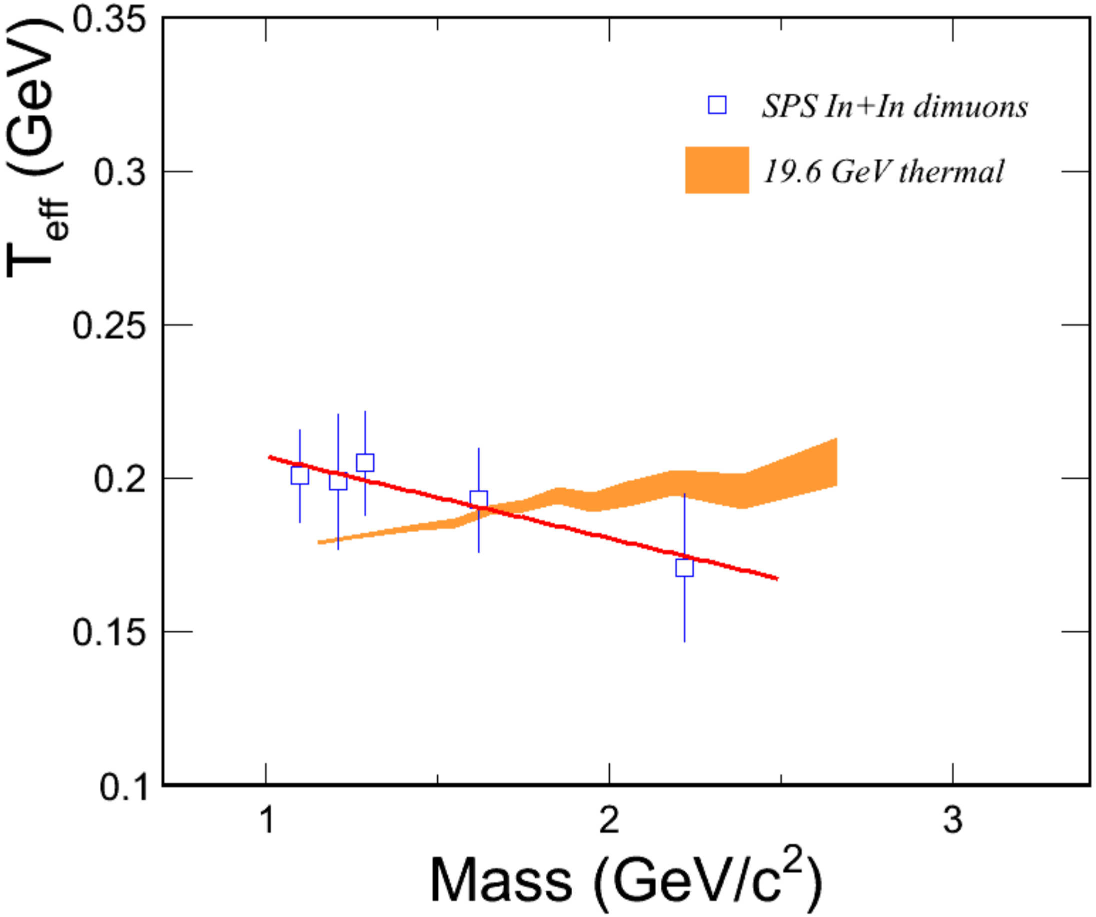
P-wave of ππ channel: $\Gamma_{\pi\pi} = \Gamma_0 \frac{M_\rho}{m_{ee}} (\frac{m_{ee}^2 - 4M_\pi^2}{M_\rho^2 - 4M_\pi^2})^{3/2},$

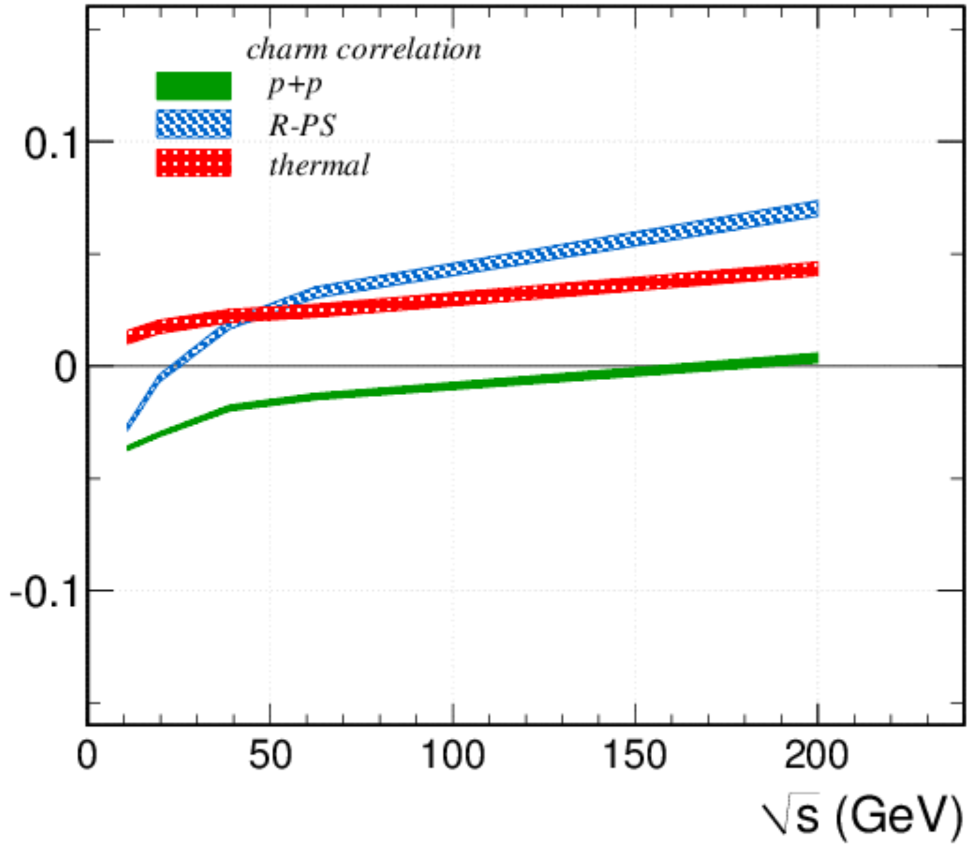
S-wave of ee channel: $\Gamma_{ee} = \Gamma_0 \frac{M_\rho}{m_{ee}} (\frac{m_{ee}^2 - 4m_e^2}{M_\rho^2 - 4m_e^2})^{1/2},$

PRC 78, 044906 (2008)
PRC 86, 024906 (2012)

$$PS = \frac{m_{ee}}{\sqrt{m_{ee}^2 + p_T^2}} e^{-\frac{\sqrt{m_{ee}^2+p_T^2}}{T}}.$$

Possible observation at phase transition?





High energy dominant by charm correlation, lower energy charm and thermal contributions are comparable.

Both T_{eff} and its slope in medium are significant higher than the system w/o medium.

Phase transition could happen if the T_{eff} increases dramatically or the sign of its slope changes from negative to positive.